Phase (check one)	Type (check one)
■ Initial Site Investigation ☐ Corrective Action Feasibility Investigation ☐ Corrective Action Plan ☐ Corrective Action Summary Report ☐ Operations and Monitoring Report	☐ Work Scope ■ Technical Report ☐ PCF Reimbursement Request ☐ General Correspondence

INITIAL SITE INVESTIGATION REPORT

Swasey Property
223 Main Street
Montpelier, VT

SEI Project No. 96-599
DEC Site No. 96~~2014~~ 2045

A Residence Owned By:
Raelene Aldrich and Mary Swasey
Montpelier, Vermont

Client:
Fred Cleveland representing
Raelene Aldrich and Mary Swasey
100 Main Street
Montpelier, VT 05602
(802) 223-3479

Prepared by:
Stone Environmental, Inc.
58 East State Street
Montpelier, VT 05602
(802) 229-4541
Contact: John Hanzas, Staff Geoscientist

November 13, 1996

EXECUTIVE SUMMARY

Stone Environmental Inc. (SEI) discovered two underground storage tanks (USTs) at 223 Main Street, Montpelier, Vermont (USTs) during a Level I Environmental Site Assessment (April 26, 1996) of the property. The exact age of the tanks is unknown but they were most likely placed on the site in the late 1920's when Capitol City Cleansers occupied the western portion of the lot. Capitol City Cleansers subsequently went out of business in 1934 and the building remained empty until 1972 when it was removed. The area is now a grassy lawn for the residence occupying the eastern portion of the site.

The two USTs were removed from the Swasey property on May 17, 1996. SEI supervised the removal, excavation, and tank cleaning performed by North Country Environmental Services and GSB Excavators. Soils surrounding both tanks were found to be contaminated. Tank 1(~1000 gallon capacity) appeared to be intact and was filled to the top with a petroleum liquid and a graphite colored sludge. Tank 2 (~300 gallon capacity)had many holes and contained water with minimal petroleum contamination. Soil contamination seems to have been caused by the leaking of tank 2, overfilling of tank 1 or a combination of both. Based on the chromatographic interpretations the contamination is from a fuel oil and some natural bioattenuation is occurring.

On July 25, 1996 SEI performed an initial site investigation to delineate the plume of contamination, determine stratigraphy of the soils and identify the direction of groundwater flow. Adams Engineering, under SEI's supervision, advanced six soil borings, installed two monitoring wells (SB-1/MW-1 and SB-5), and installed four temporary wells (SB-2, 3, 4, and 6). Groundwater samples were collected and submitted to Green Mountain Laboratories of Middlesex, Vermont for EPA Method 8260 analysis. Laboratory results for SB-1/MW-1, SB-2 and SB-6 revealed no detections for all 8260 parameters. SB-3 was not sampled due to a visible sheen on the water table. SB-5 had detections of ethylbenzene, isopropylbenzene, napthalene, n-propylbenzene, toluene, trimethylbenzenes, and xylenes. Only total xylenes exceeded the Vermont Groundwater Enforcement Standards. Based on the site survey and depth to water measurements performed by SEI, the groundwater flow direction mimics topography and flows to the southwest with a gradient of 0.09 ft/ft.

This report recommends further investigation of the Whittier Street sewer line as a potential receptor of contaminated groundwater and remediation of the soil and groundwater contamination following a Corrective Action Feasibility Investigation. Recommended components of the Corrective Action Feasibility Investigation are contained in section 6.0 of the report.

1.0 INTRODUCTION

The Estate of Richard Swasey and Raelene Aldrich, co-owners of the Swasey property located at 223 Main Street in Montpelier (see Figure 1), contracted with SEI through McKee, Guiliani, and Cleveland to perform a Level I ESA at the property. The ESA (April 26, 1996) revealed two USTs in the side yard of the residence, behind the former location of Capital City Cleansers (see Figure 2). The USTs were subsequently removed and their contents properly disposed of (see Attachment C). Contaminated soils were discovered during the tank removal and it became apparent that further investigation of the site was required. The initial site investigation was performed on July 27, 1996 in an effort to delineate the contamination and further characterize the site. This report describes the methods used in the investigation and presents all field and laboratory results.

2.0 METHODS AND MATERIALS

2.1 Soil Borings

Adams Engineering of Underhill, Vermont advanced all borings on July 27, 1996 under the technical guidance of SEI. A total of six soil borings were advanced per SEI Standard Operating Procedure (SOP) 6.10.2. Soil borings were advanced in 5 foot increments using Adams' vibratory sampler. A plastic sleeve was placed within the spoon to enhance sample recovery.

The soils were characterized and logged at textural changes per SEI SOP 6.17.1 (see Table 1).

Soil borings were not advanced within the area of the tanks' excavation due to the confirmation of significant soil contamination discovered during the tank removal (see Attachment C). The soil contamination in this area is corroborated by visual and olfactory observations, PID readings during the removal of the tanks, and a soil sample take by hand auger on July 11, 1996 (described below).

2.2 Hand Augered Soil Borings

Using a hand auger SEI sampled the soils at a depth of 3.5 feet between the two excavations on July 11, 1996. This sample was taken at the request of Maria Stadlmayer of the State of Vermont Department of Environmental Conservation (DEC) Sites Management Section (SMS) in order to determine the contamination which was actually impacting the soils.

SEI advanced an additional soil boring (SB-7) in Ellin Perry's backyard (see Figure 2)on September 17, 1996. A temporary well was installed and the soils were characterized and logged. This boring was advanced in response to Ellin Perry's concern that contaminated groundwater may be flowing into her basement.

2.3 Photoionization Detector (PID) Measurements

The soils within each 5 foot section of borings performed by Adams Engineering were sampled at either textural changes or approximate 1 foot increments. The samples were sealed in Ziplock® bags, the soil was crushed and shaken in order to volatilize any trapped vapor, and allowed to equilibrate for

a minimum of 5 minutes. SEI then measured VOCs from the sample headspace using a MiniRae® PID equipped with a 10.6eV lamp.

PID readings were also taken in the basements of the residences on the Swasey and Carr properties on July 27, 1996 and at the Perry property on September 6, 1996.

2.4 Groundwater Sampling

Two permanent 1.5 inch ID PVC monitoring wells with five feet of 0.010 inch screen were installed in soil borings SB-1 and SB-5 (see Figure 3). Four temporary 1.0 inch ID wire wrapped, stainless steel wells with five feet of 0.010 inch screen were installed in each of the other soil borings. Each well was developed and sampled using a dedicated disposable bailer. SB-3 was not developed nor sampled due to a hydrocarbon sheen observed in the well. The samples were placed on ice and delivered to Green Mountain Laboratories at the end of the day.

Groundwater in SB-7 was sampled on September 17,1996 using a temporary well and disposable bailer. The sample was preserved on ice and delivered to Green Mountain Laboratories on that same date.

3.0 HYDROGEOLOGY

According to the *Surficial Geologic Map of Vermont* (1970) this site was within the extent of glacial Lake Vermont. The stratigraphy of the top 10 feet of soils at the site are consistent with a typical glacial lake sequence transitioning to a fluvial environment. There is a basal clay layer of unknown vertical extent overlain by a sandy loam with varying clay content. A crossection along A-A' from Figure 3 is included in Figure 4. This crossection provides a unique view of the soil stratigraphy, as well as the position of the potentiometric surface (described below). The crossection was drawn through SB-2 and SB-4 and the closest soil borings were projected onto the crossection line. This crossection is consistent with the stratigraphy of soils characterized during the tank removal.

A perched aquifer was encountered at approximately 3 feet below ground surface (bgs). Based on the stratigraphy at the site and the discrepancy between the water level in the soil borings (Table 1) and the water level measurements taken in the wells it is believed that this aquifer is under pressure, therefore the water level measurements are describing a potentiometric surface not the water table. The aquifer was approximately 4- 5 feet thick. This aquifer (believed to be ephemeral) yielded no water during the UST removal in May. Its presence during the drilling was likely due to the unusually high amounts of precipitation received to that point in the year. According to Roger Hill, weather station manager for the Berlin Airport, rainfall in Montpelier for June and July was 5.05 inches above the historical average.

Based on a site survey and depth to water measurements collected on July 27, 1996 by SEI, the groundwater flow direction appears to mimic topography and flow to the southwest with an average gradient of 9 percent. Groundwater contours at one foot intervals are provided in Figure 2. The depth to water in SB-6 is questionable because the well may not have been given sufficient time to equilibrate after development. As a result, the gradient of the potentiometric surface in the area of SB-6 may not be as steep as represented in Figure 2.

4.0 RESULTS AND DISCUSSION

4.1 Soils

Soils screened, with the PID, from SB-1, SB-2, SB-4, SB-6 and SB-7 had no significant detections of VOCs. Soils screened, with the PID, from SB-3 and SB-5 revealed high levels of VOCs from 1 to 7 feet (298 ppm peak) and from 2 to 6 feet (102 ppm peak), respectively. Headspace analyses of each soil boring are included in Table 2.

The soil sample collected by hand auger from between the excavations had detections of butylbenzenes, ethylbenzene, isopropylbenzene, p-isoproppyltoluene, napthalene, n-propylbenzene, trimethylbenzenes, and xylenes (see Attachment A, sample labeled "front yard").

4.2 Groundwater

No EPA Method 8260 (8260) parameters were detected in samples from SB-1(MW-1), SB-2, SB-6 or SB-7. SB-3 was not sampled due to a visible hydrocarbon sheen on the water table. SB-5 had detections of ethylbenzene, isopropylbenzene, napthalene, n-propylbenzene, toluene, trimethylbenzenes, and xylenes. Only total xylenes exceeded the Vermont Groundwater Enforcement Standards. A summary of the groundwater sampling results are included in Table 3, and copies of the results from the lab are included in Attachment A.

There was a correlative relationship between lab analyses and field screening of soils for all soil borings with the exception of SB-4. No significant detections of VOCs were measured by PID in SB-4, yet the laboratory detected MTBE in the groundwater. All other 8260 parameters were ND for this sample. There have been significant detections of other 8260 parameters, but MTBE has never been detected at this site previous to this sample. For this reason SEI suspects that this detection is the result of activities related to the gravel driveway which is located approximately 3 feet from the well. Another factor which leads SEI to this conclusion is the fact that MTBE is a relatively new chemical and the contamination on this site is known to have originated in the late 1920's or early 1930's.

Chromatographic interpretations of the soil and groundwater analysis, performed by John Amadon, an independent consultant (see Attachment B), indicate that the contamination in their soils is a fuel oil and that it has undergone some amount of natural biodegradation.

5.0 POTENTIAL RECEPTORS ASSESSMENT

SEI has investigated all the basements surrounding the plume of contamination with its MiniRae® PID equipped with a 10.6eV lamp. There were no detections of VOCs in any of the surrounding basements. Groundwater was noted to be slowly seeping into the basements of the Carr's and Perry's houses which are located to the southeast and southwest of the site (downgradient) and no VOCs were detected in their basements.

An avenue which has not yet been investigated is the presence of a possible preferential conduit in the fill surrounding the sewer line beneath Whittier Street. This conduit may be intercepting the groundwater contamination and may be responsible for the lack of contamination on the Perry property, located across Whittier Street.

The records at the Water Supply Division of the Vermont Department of Environmental Conservation show no public water supply wells located within 500 feet of the site. All residences in the area are connected to town water lines.

6.0 CONCLUSIONS / RECOMMENDATIONS

1) The contaminated soil initially encountered during the UST removal does extend hydraulically downgradient to Whittier Street.

2) Groundwater has been adversely impacted and product sheens have been observed in SB-3.

3) The contaminant appears to be primarily a weathered fuel oil exhibiting evidence of biodegradation.

4) The contaminant has not yet migrated to downgradient residential properties although potential preferential conduits within Whittier Street remain unknown.

5) Contaminant migration vertically appears to be impeded by a native clay layer.

6) The receptor assessment has shown a potential for horizontal downgradient impacts at the Perry and Carr residences.

7) Remediation of the soil and groundwater contamination is warranted following a Corrective Action Feasibility Investigation (CAFI).

8) Components of the CAFI should include:

   a) enhanced site monitoring for liquid level fluctuations and water quality assays for contaminants and biodegradation indicators;

   b) detailed review of Whittier Street utilities/preferential conduits;

   c) evaluation of the impeding native clay layer and regional hydrogeology; and

   d) evaluation of corrective action alternatives (excavation, conventional groundwater treatment, vapor extraction/sparging, bioventing, nutrient/a.e.a additions, natural attenuation and monitoring).

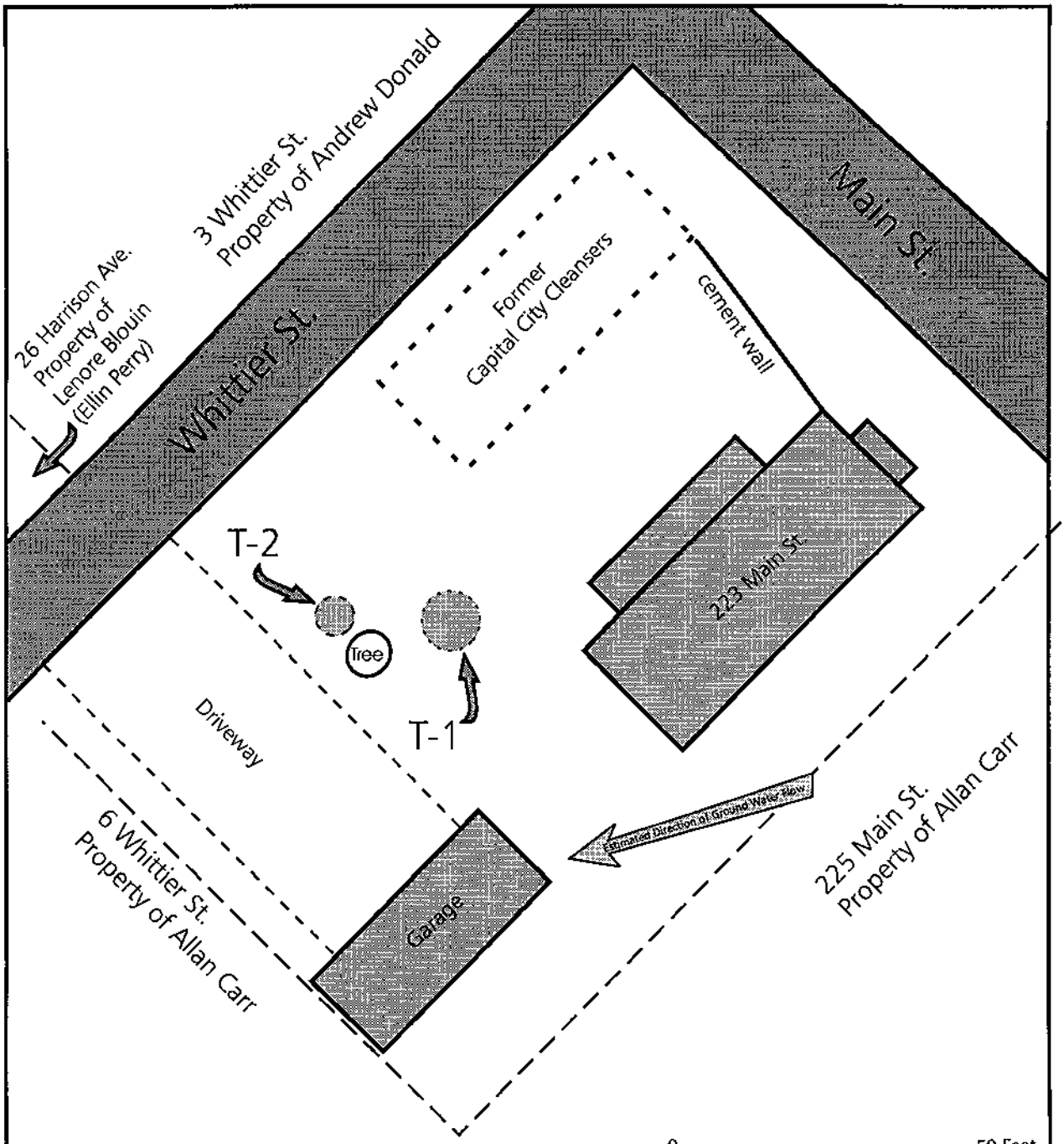

FIGURE 2: SITE MAP
223 Main Street
Montpelier, Vermont

Source: SEI Site Visit
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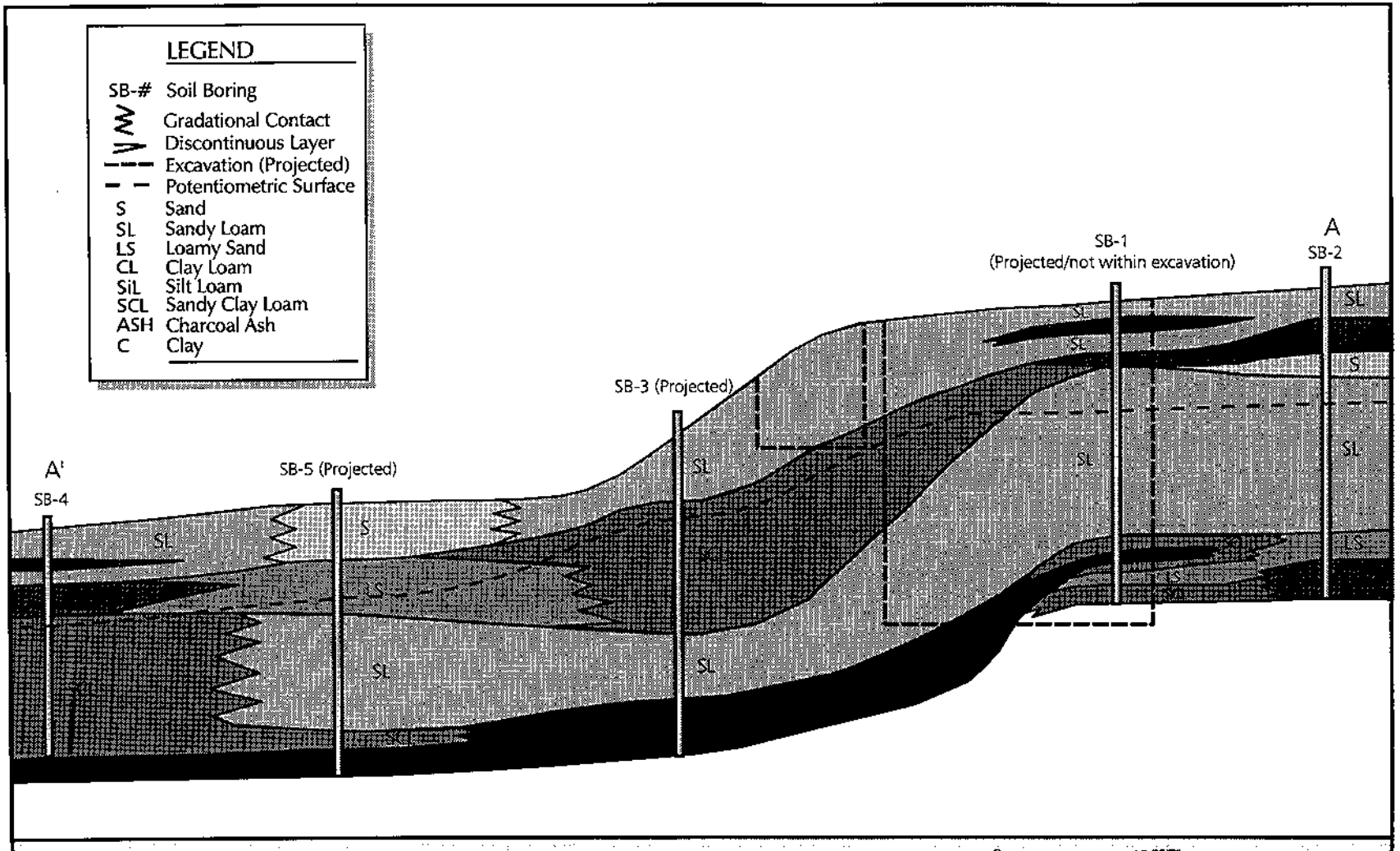

FIGURE 4: CROSS SECTION A - A'
223 Main Street
Montpelier, Vermont

0 10 FEET
Vertical Exaggeration X2
2 FEET

Source: SEI Survey and Field Notes
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int:7-31-96jph

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TABLE 1
Swasey Property
Soil Boring Logs

SB-1

Depth	Soil Type
First Spoon (0.0-5.0')	36" recovery
0.0 - 6.0"	top soil, sandy loam
6.0 - 12.0"	clay loam
12.0 - 18.0"	sandy loam
18.0 - 22.0"	ash mixed with clay loam
22.0 - 36.0"	sandy loam - moist
Second Spoon (5.0-10.0'	48" recovery
0.0 - 30.0"	sandy loam - wet
30.0 - 36.0"	sandy clay loam - wet
36.0 - 41.0"	clay (mottled) - moist
41.0 - 44.0"	loamy sand - moist
44.0 - 48.0"	sandy clay loam - moist

SB-2

Depth	Soil Type
First Spoon (0.0-5.0')	40" recovery
0.0 - 12.0"	sandy loam
12.0 - 24.0"	ash layer
24.0 - 32.0"	sand - moist
32.0 - 40.0"	fine sandy loam
Second Spoon (5.0-10.0'	60" recovery
0.0 - 32.0"	sandy loam
32.0 - 43.0"	sand / loamy sand
43.0 - 60.0"	silt loam

SB-3

Depth	Soil Type
First Spoon (0.0-5.0')	40" recovery
0.0 - 18.0"	sandy loam, gravel
18.0 - 24.0"	sandy loam - dark color, petroleum odor
24.0 - 32.0"	sandy clay loam - petroleum odor
32.0 - 34.0"	sandy loam - petroleum odor
34.0 - 48.0"	sandy clay loam - petroleum odor
Second Spoon (5.0-10.0'	54" recovery
0.0 - 16.0"	sandy clay loam - wet, sheen on top
16.0 - 36.0"	sandy loam - wet, dark staining 29 - 31"
36.0 - 54.0"	clay - moist

SB-4

Depth	Soil Type
First Spoon (0.0-5.0')	48" recovery
0.0 - 10.0"	sandy loam, top soil
10.0 - 14.0"	ash, sandy
14.0 - 20.0"	sandy loam
20.0 - 32.0"	silt loam
32.0 - 48.0"	sandy clay loam
Second Spoon (5.0-7.3')	refusal at 7.3'
0.0 - 4.0"	sandy clay loam - moist
4.0 - 24.3"	sandy loam to sandy clay loam - wet

SB-5

Depth	Soil Type
First Spoon (0.0-5.0')	40" recovery
0.0 - 1.0"	topsoil
1.0 - 20.0"	sand and gravel - driveway fi
20.0 - 30.0"	loamy sand/sandy loam - stained, petroleum odor
30.0 - 40.0"	loamy sandy - moist
Second Spoon (5.0-14	4" recovery
0.0 - 25.0"	sandy loam - wet with sheen
25.0 - 32.0"	sandy clay loam - wet, wood at 32 - 34"
32.0 - 44.0"	clay - moist

SB-6

Depth	Soil Type
First Spoon (0.0-5.0')	36" recovery
0.0 - 3.0"	topsoil
3.0 - 16.0"	loamy sandy
16.0 - 19.0"	sandy loam
19.0 - 20.0"	ash
20.0 - 25.0"	crushed rock (phyllite)
25.0 - 36.0"	clay - moist
Second Spoon (5.0-13	6" recovery
0.0 - 10.0"	silty clay - moist
10.0 - 18.0"	sandy loam - wet
18.0 - 22.0"	loamy sand - wet
22.0 - 26.0"	sandy loam - wet
26.0 - 30.0"	sand - red mottling, wet
30.0 - 36.0"	clay - moist

SB-7

Depth	Soil Type
First Spoon (0.0-2.0')	
0.0 - 12.0"	top soil, sandy loam, brick la
12.0 - 16.0"	sandy loam - wet
16.0 - 21.0"	clay (mottled) - moist

Source: SEI Field Notes
jph 8-02-96

TABLE 3
Swasey Property
Summary of the Results of Groundwater Sampling - EPA Method 8260

	PARAMETERS										
Sample ID	**Benzene**	**Toluene**	**Ethylbenzene**	**m+p-Xylene**	**o-Xylene**	**MTBE**	**Isopropylbenzene**	**Naphthalene**	**n-Propylbenzene**	**1,2,4-Trimethylbenzene**	**1,3,5-Trimethylbenzene**
Front Yard	ND	ND	**91**	**380**	**140**	ND	53	250	100	1600	1900
MW-1/SB-1(ug/l)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-2(ug/l)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-4(ug/l)	ND	ND	ND	ND	ND	190	ND	ND	ND	ND	ND
SB-5(ug/l)	ND	22	**250**	1300	400	ND	54	270	78	660	230
SB-6(ug/l)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-7(ug/l)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
GWES (ug/l)	5.0	2420	6		400	none	none	none	none	none	none

Notes: -shaded areas delineate total of shaded row parameters
-GWES = Vermont Groundwater Enforcement Standard
- ug/l = micrograms per liter, or parts per billion
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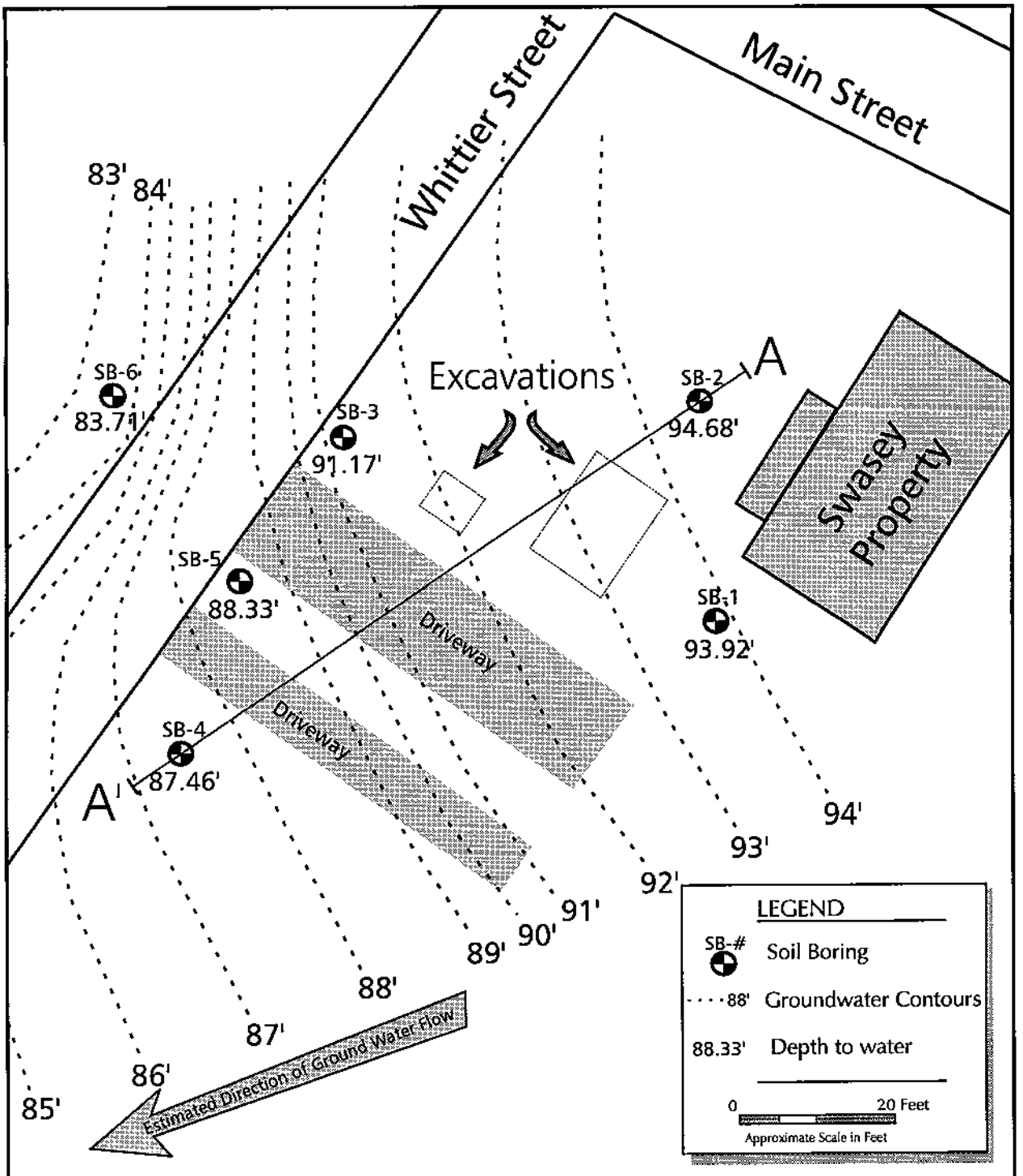

FIGURE 3: GROUNDWATER CONTOUR MAP
223 Main Street
Montpelier, Vermont

Source: SEI Survey and Field Notes 1996
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int: 7-30-96 jms

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TABLE 2
Swasey Property
Soil Boring PID Readings

SB-1

Depth	PID Reading (ppm) peak/sustained
First Spoon (0.0-5.0')	
0.0 - 12.0"	0.0
12.0 - 24.0"	0.0
24.0 - 36.0"	1.1/0.0
plug	1.9/0.0
Second Spoon (5.0-10.0')	
0.0 - 12.0"	1.8/0.0
12.0 - 24.0"	0.1/0.0
24.0 - 36.0"	0.0
36.0 - 48.0"	0.0
plug	1.2/0.0

SB-2

Depth	PID Reading (ppm) peak/sustained
First Spoon (0.0-5.0')	
0.0 - 12.0"	0.0
12.0 - 24.0"	0.0
24.0 - 36.0"	0.1/0.0
Second Spoon (5.0-10.0')	
0.0 - 12.0"	0.0
12.0 - 24.0"	0.1/0.0
24.0 - 36.0"	0.0
36.0 - 48.0"	0.0
48.0 - 60.0"	0.1/0.0

SB-3

Depth	PID Reading (ppm) peak/sustained
First Spoon (0.0-5.0')	
0.0 - 12.0"	1.6/1.4
12.0 - 24.0"	298/264
24.0 - 36.0"	206/198
36.0 - 48.0"	241/198
Second Spoon (5.0-10.0')	
0.0 - 12.0"	234/115
12.0 - 24.0"	60/30
24.0 - 36.0"	6/4.5
36.0 - 48.0"	3.6/1.5
48.0 - 54.0"	2.8/2.8

SB-4

Depth	PID Reading (ppm) peak/sustained
First Spoon (0.0-5.0')	
0.0 - 12.0"	0.7/0.5
12.0 - 24.0"	0.5/0.5
24.0 - 36.0"	0.9/0.7
36.0 - 48.0"	1.5/1.2
plug	1.7/1.3
Second Spoon (5.0-10.0')	
0.0 - 12.0"	0.8/0.7
12.0 - 24.0"	1.0/1.0

SB-5

Depth	PID Reading (ppm) peak/sustained
First Spoon (0.0-5.0')	
0.0 - 12.0"	5.1/3.4
12.0 - 20.0"	3.0/3.0
20.0 - 30.0"	102.6/101.0
30.0 - 40.0"	93.7/92.0
Second Spoon (5.0-10.0')	
0.0 - 12.0"	76/33
12.0 - 24.0"	7.1/7.0
24.0 - 36.0"	3.9/3.3
36.0 - 48.0"	3.0/3.0
48.0 - 54.0"	2.8/2.8

SB-6

Depth	PID Reading (ppm) peak/sustained
First Spoon (0.0-5.0')	
0.0 - 12.0"	1.0/1.0
12.0 - 24.0"	1.2/1.1
24.0 - 36.0"	0.8/0.8
Second Spoon (5.0-10.0')	
0.0 - 12.0"	1.0/1.0
12.0 - 24.0"	1.0/1.0
24.0 - 36.0"	1.0/1.0

SB-7

Depth	PID Reading (ppm) peak/sustained
Auger(0.0-2.0')	
0.0 - 12.0"	0.5/0.4
12.0 - 18.0"	0.6/0.5
18.0 - 24.0"	1.3/1.1

Source: SEI Field Notes
jph 8-02-96

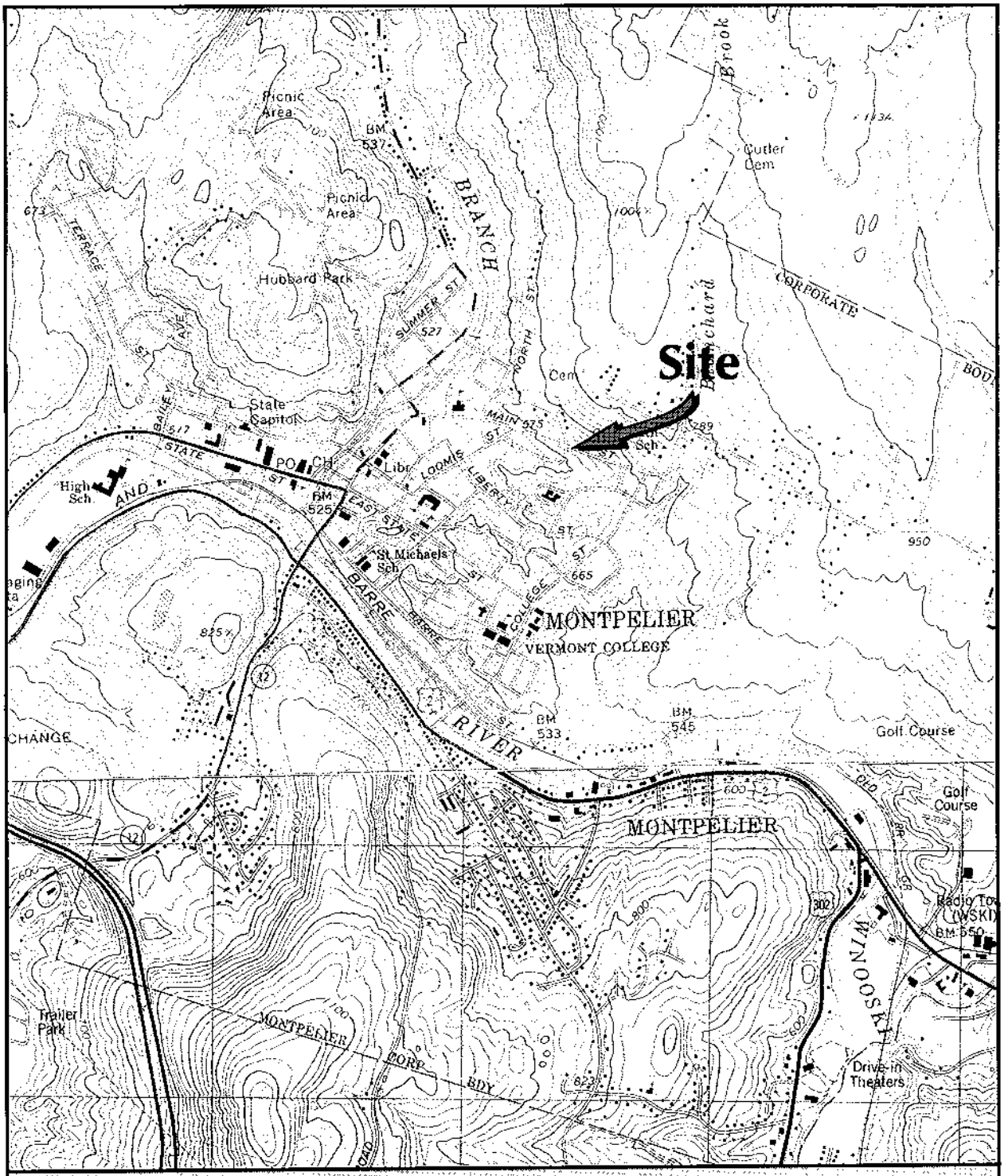

FIGURE 1: SITE LOCATION MAP
223 Main Street
Montpelier, Vermont

0 ½ MILE
Approximate Scale in Miles
Contour Interval 6 Meters

Source: Montpelier, VT Quadrangle, 7.5 Minute Series, 1:24,000 Scale, USGS 1968;
Barre West, VT Quadrangle, 7.5 Minute Series, 1:24,000 Scale, USGS 1988

STONE ENVIRONMENTAL INC

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GREEN MOUNTAIN LABORATORIES, INC.

RR 3, BOX 5210
Montpelier, Vermont 05602

Phone (802) 223 - 1468 Fax (802) 223 - 8688

LABORATORY RESULTS

CLIENT NAME:	Stone Environmental, Inc.	REFERENCE NO.:	1069
ADDRESS:	58 E. State Street	PROJECT NO.:	95-599
	Montpelier, VT 05602	DATE OF SAMPLE:	07/25/96
SAMPLE LOCATION:	223 Main St.	DATE OF RECEIPT:	07/25/96
SAMPLER:	John Hanzas/Jeff Kelley	DATE OF ANALYSIS:	07/31/96
ATTENTION:	John Hanzas	DATE OF REPORT:	07/31/96

Pertaining to the analyses of specimens submitted under the accompanying chain of custody form, please note the following:

- Water samples submitted for VOC analysis were preserved with HCl in the laboratory.
- Specimens were processed and examined according to the procedures outlined in the specified method.
- Holding times were honored.
- Instruments were appropriately tuned and calibrations were checked with the frequencies required in the specified method.
- Blank contamination was not observed at levels interfering with the analytical results.
- Continuing Calibration standards were monitored at intervals indicated in the specified method. The resulting analytical precision and accuracy were determined to be within method QA/QC acceptance limits.
- The efficiency of analyte recovery for individual samples was monitored by the addition of surrogate analyte to all samples, standards, and blanks. Surrogate recoveries were found to be within laboratory QA/QC acceptance limits, unless noted otherwise.

Reviewed by:

Althea L. Lindell

Althea L. Lindell
Director, Chemical Services

Green Mountain Laboratories, Inc.

RR 3, Box 5210
Montpelier, Vermont 05602

Phone (802) 223-1468 Fax (802) 223-8688

GML REF. # : 1011
STATION: FRONT YARD
ANALYSIS DATE: 07/17/96
DATE SAMPLED: 07/11/96
SAMPLE TYPE: SOIL (78.9% DRY WT.)

PARAMETERS	PQL	µg/kg
Benzene	24	ND
Bromobenzene	24	ND
Bromochloromethane	72	ND
Bromodichloromethane	24	ND
Bromoform	24	ND
Bromomethane	120	ND
n-Butylbenzene	48	270
sec-Butylbenzene	24	130
tert-Butylbenzene	48	50
Carbon Tetrachloride	24	ND
Chlorobenzene	24	ND
Chloroethane	48	ND
Chloroform	24	ND
Chloromethane	48	ND
o-Chlorotoluene	24	ND
p-Chlorotoluene	48	ND
1,2-Dibromo-3-chloropropan	72	ND
Dibromochloromethane	48	ND
1,2-Dibromomethane (EDB)	24	ND
Dibromomethane	24	ND
o-Dichlorobenzene	24	ND
m-Dichlorobenzene	24	ND
p-Dichlorobenzene	24	ND
Dichlorodifluoromethane	48	ND
1,1-Dichloroethane	48	ND
1,2-Dichloroethane	24	ND
1,1-Dichloroethylene	24	ND
cis-1,2-Dichloroethylene	48	ND
trans-1,2-Dichloroethylene	48	ND
1,2-Dichloropropane	24	ND
1,3-Dichloropropane	24	ND
2,2-Dichloropropane	48	ND
1,1-Dichloropropene	24	ND
cis-1,3-Dichloropropene	24	ND

PARAMETERS	PQL	µg/kg
trans-1,3-Dichloropropene	24	ND
Ethylbenzene	24	91
Hexachlorobutadiene	240	ND
Isopropylbenzene	24	53
p-Isopropyltoluene	48	510
Methylene Chloride	120	ND
Methyl-t-butyl-ether (MTBE)	48	ND
Naphthalene	120	250
n-Propylbenzene	24	100
Styrene	48	ND
1,1,1,2-Tetrachloroethane	24	ND
1,1,2,2-Tetrachloroethane	48	ND
Tetrachloroethylene	24	ND
Toluene	24	ND
1,2,3-Trichlorobenzene	48	ND
1,2,4-Trichlorobenzene	48	ND
1,1,1-Trichloroethane	24	ND
1,1,2-Trichloroethane	24	ND
Trichloroethylene (TCE)	24	ND
Trichlorofluoromethane	48	ND
1,2,3-Trichloropropane	48	ND
1,2,4-Trimethylbenzene	24	1600
1,3,5-Trimethylbenzene	24	1900
Vinyl Chloride	48	ND
o-Xylene	24	140
m + p-Xylene	48	380

Surrogates:	
Dibromofluoromethane	99.3 %
Toluene-D8	106 %
4-Bromofluorobenzene	121 %

ND - Not Detected
Concentration units = µg/kg

Green Mountain Laboratories, Inc.

RR 3, Box 5210

Montpelier, Vermont 05602

Phone (802) 223-1468 Fax (802) 223-8688

GML REF. # : 1069
STATION: MW-1
ANALYSIS DATE: 07/31/96
DATE SAMPLED: 07/25/96
SAMPLE TYPE: WATER

PARAMETERS	PQL	µg/L
Benzene	1	ND
Bromobenzene	1	ND
Bromochloromethane	3	ND
Bromodichloromethane	1	ND
Bromoform	1	ND
Bromomethane	5	ND
n-Butylbenzene	2	ND
sec-Butylbenzene	1	ND
tert-Butylbenzene	2	ND
Carbon Tetrachloride	1	ND
Chlorobenzene	1	ND
Chloroethane	2	ND
Chloroform	1	ND
Chloromethane	2	ND
o-Chlorotoluene	1	ND
p-Chlorotoluene	2	ND
1,2-Dibromo-3-chloropropan	3	ND
Dibromochloromethane	2	ND
1,2-Dibromomethane (EDB)	1	ND
Dibromomethane	1	ND
o-Dichlorobenzene	1	ND
m-Dichlorobenzene	1	ND
p-Dichlorobenzene	1	ND
Dichlorodifluoromethane	2	ND
1,1-Dichloroethane	2	ND
1,2-Dichloroethane	1	ND
1,1-Dichloroethylene	1	ND
cis-1,2-Dichloroethylene	2	ND
trans-1,2-Dichloroethylene	2	ND
1,2-Dichloropropane	1	ND
1,3-Dichloropropane	1	ND
2,2-Dichloropropane	2	ND
1,1-Dichloropropene	1	ND
cis-1,3-Dichloropropene	1	ND

PARAMETERS	PQL	µg/L
trans-1,3-Dichloropropene	1	ND
Ethylbenzene	1	ND
Hexachlorobutadiene	10	ND
Isopropylbenzene	1	ND
p-Isopropyltoluene	2	ND
Methylene Chloride	5	ND
Methyl-t-butyl-ether (MTBE)	2	ND
Naphthalene	5	ND
n-Propylbenzene	1	ND
Styrene	2	ND
1,1,1,2-Tetrachloroethane	1	ND
1,1,2,2-Tetrachloroethane	2	ND
Tetrachloroethylene	1	ND
Toluene	1	ND
1,2,3-Trichlorobenzene	2	ND
1,2,4-Trichlorobenzene	2	ND
1,1,1-Trichloroethane	1	ND
1,1,2-Trichloroethane	1	ND
Trichloroethylene (TCE)	1	ND
Trichlorofluoromethane	2	ND
1,2,3-Trichloropropane	2	ND
1,2,4-Trimethylbenzene	1	ND
1,3,5-Trimethylbenzene	1	ND
Vinyl Chloride	2	ND
o-Xylene	1	ND
m + p-Xylene	2	ND
Surrogates:		
Dibromofluoromethane	122 %	
Toluene-D8	105 %	
4-Bromofluorobenzene	86.4 %	

ND - Not Detected
Concentration units = µg/L

Green Mountain Laboratories, Inc.

RR 3, Box 5210

Montpelier, Vermont 05602

Phone (802) 223-1468 Fax (802) 223-8688

GML REF. # : 1069
STATION: SB-2
ANALYSIS DATE: 07/31/96
DATE SAMPLED: 07/25/96
SAMPLE TYPE: WATER

PARAMETERS	PQL	µg/L	PARAMETERS	PQL	µg/L
Benzene	1	ND	trans-1,3-Dichloropropene	1	ND
Bromobenzene	1	ND	Ethylbenzene	1	ND
Bromochloromethane	3	ND	Hexachlorobutadiene	10	ND
Bromodichloromethane	1	ND	Isopropylbenzene	1	ND
Bromoform	1	ND	p-Isopropyltoluene	2	ND
Bromomethane	5	ND	Methylene Chloride	5	ND
n-Butylbenzene	2	ND	Methyl-t-butyl-ether (MTBE)	2	ND
sec-Butylbenzene	1	ND	Naphthalene	5	ND
tert-Butylbenzene	2	ND	n-Propylbenzene	1	ND
Carbon Tetrachloride	1	ND	Styrene	2	ND
Chlorobenzene	1	ND	1,1,1,2-Tetrachloroethane	1	ND
Chloroethane	2	ND	1,1,2,2-Tetrachloroethane	2	ND
Chloroform	1	ND	Tetrachloroethylene	1	ND
Chloromethane	2	ND	Toluene	1	ND
o-Chlorotoluene	1	ND	1,2,3-Trichlorobenzene	2	ND
p-Chlorotoluene	2	ND	1,2,4-Trichlorobenzene	2	ND
1,2-Dibromo-3-chloropropan	3	ND	1,1,1-Trichloroethane	1	ND
Dibromochloromethane	2	ND	1,1,2-Trichloroethane	1	ND
1,2-Dibromomethane (EDB)	1	ND	Trichloroethylene (TCE)	1	ND
Dibromomethane	1	ND	Trichlorofluoromethane	2	ND
o-Dichlorobenzene	1	ND	1,2,3-Trichloropropane	2	ND
m-Dichlorobenzene	1	ND	1,2,4-Trimethylbenzene	1	ND
p-Dichlorobenzene	1	ND	1,3,5-Trimethylbenzene	1	ND
Dichlorodifluoromethane	2	ND	Vinyl Chloride	2	ND
1,1-Dichloroethane	2	ND	o-Xylene	1	ND
1,2-Dichloroethane	1	ND	m + p-Xylene	2	ND
1,1-Dichloroethylene	1	ND			
cis-1,2-Dichloroethylene	2	ND	Surrogates:		
trans-1,2-Dichloroethylene	2	ND	Dibromofluoromethane	113 %	
1,2-Dichloropropane	1	ND	Toluene-D8	106 %	
1,3-Dichloropropane	1	ND	4-Bromofluorobenzene	90.3 %	
2,2-Dichloropropane	2	ND			
1,1-Dichloropropene	1	ND	ND - Not Detected		
cis-1,3-Dichloropropene	1	ND	Concentration units = µg/L		

Green Mountain Laboratories, Inc.

RR 3, Box 5210

Montpelier, Vermont 05602

Phone (802) 223-1468 Fax (802) 223-8688

GML REF. # : 1069
STATION: SB-4
ANALYSIS DATE: 07/31/96
DATE SAMPLED: 07/25/96
SAMPLE TYPE: WATER

PARAMETERS	PQL	µg/L	PARAMETERS	PQL	µg/L
Benzene	1	ND	trans-1,3-Dichloropropene	1	ND
Bromobenzene	1	ND	Ethylbenzene	1	ND
Bromochloromethane	3	ND	Hexachlorobutadiene	10	ND
Bromodichloromethane	1	ND	Isopropylbenzene	1	ND
Bromoform	1	ND	p-Isopropyltoluene	2	ND
Bromomethane	5	ND	Methylene Chloride	5	ND
n-Butylbenzene	2	ND	Methyl-t-butyl-ether (MTBE)	2	190
sec-Butylbenzene	1	ND	Naphthalene	5	ND
tert-Butylbenzene	2	ND	n-Propylbenzene	1	ND
Carbon Tetrachloride	1	ND	Styrene	2	ND
Chlorobenzene	1	ND	1,1,1,2-Tetrachloroethane	1	ND
Chloroethane	2	ND	1,1,2,2-Tetrachloroethane	2	ND
Chloroform	1	ND	Tetrachloroethylene	1	ND
Chloromethane	2	ND	Toluene	1	ND
o-Chlorotoluene	1	ND	1,2,3-Trichlorobenzene	2	ND
p-Chlorotoluene	2	ND	1,2,4-Trichlorobenzene	2	ND
1,2-Dibromo-3-chloropropan	3	ND	1,1,1-Trichloroethane	1	ND
Dibromochloromethane	2	ND	1,1,2-Trichloroethane	1	ND
1,2-Dibromomethane (EDB)	1	ND	Trichloroethylene (TCE)	1	ND
Dibromomethane	1	ND	Trichlorofluoromethane	2	ND
o-Dichlorobenzene	1	ND	1,2,3-Trichloropropane	2	ND
m-Dichlorobenzene	1	ND	1,2,4-Trimethylbenzene	1	ND
p-Dichlorobenzene	1	ND	1,3,5-Trimethylbenzene	1	ND
Dichlorodifluoromethane	2	ND	Vinyl Chloride	2	ND
1,1-Dichloroethane	2	ND	o-Xylene	1	ND
1,2-Dichloroethane	1	ND	m + p-Xylene	2	ND
1,1-Dichloroethylene	1	ND			
cis-1,2-Dichloroethylene	2	ND	Surrogates:		
trans-1,2-Dichloroethylene	2	ND	Dibromofluoromethane	124 %	
1,2-Dichloropropane	1	ND	Toluene-D8	107 %	
1,3-Dichloropropane	1	ND	4-Bromofluorobenzene	86.5 %	
2,2-Dichloropropane	2	ND			
1,1-Dichloropropene	1	ND	ND - Not Detected		
cis-1,3-Dichloropropene	1	ND	Concentration units = µg/L		

Green Mountain Laboratories, Inc.

RR 3, Box 5210

Montpelier, Vermont 05602

Phone (802) 223-1468 Fax (802) 223-8688

GML REF. # : 1069
STATION: SB-5
ANALYSIS DATE: 07/31/96
DATE SAMPLED: 07/25/96
SAMPLE TYPE: WATER

PARAMETERS	PQL	µg/L
Benzene	10	ND
Bromobenzene	10	ND
Bromochloromethane	30	ND
Bromodichloromethane	10	ND
Bromoform	10	ND
Bromomethane	50	ND
n-Butylbenzene	20	ND
sec-Butylbenzene	10	ND
tert-Butylbenzene	20	ND
Carbon Tetrachloride	10	ND
Chlorobenzene	10	ND
Chloroethane	20	ND
Chloroform	10	ND
Chloromethane	20	ND
o-Chlorotoluene	10	ND
p-Chlorotoluene	20	ND
1,2-Dibromo-3-chloropropan	30	ND
Dibromochloromethane	20	ND
1,2-Dibromomethane (EDB)	10	ND
Dibromomethane	10	ND
o-Dichlorobenzene	10	ND
m-Dichlorobenzene	10	ND
p-Dichlorobenzene	10	ND
Dichlorodifluoromethane	20	ND
1,1-Dichloroethane	20	ND
1,2-Dichloroethane	10	ND
1,1-Dichloroethylene	10	ND
cis-1,2-Dichloroethylene	20	ND
trans-1,2-Dichloroethylene	20	ND
1,2-Dichloropropane	10	ND
1,3-Dichloropropane	10	ND
2,2-Dichloropropane	20	ND
1,1-Dichloropropene	10	ND
cis-1,3-Dichloropropene	10	ND

PARAMETERS	PQL	µg/L
trans-1,3-Dichloropropene	10	ND
Ethylbenzene	10	250
Hexachlorobutadiene	100	ND
Isopropylbenzene	10	54
p-Isopropyltoluene	20	BPQL
Methylene Chloride	50	ND
Methyl-t-butyl-ether (MTBE)	20	ND
Naphthalene	50	270
n-Propylbenzene	10	78
Styrene	20	ND
1,1,1,2-Tetrachloroethane	10	ND
1,1,2,2-Tetrachloroethane	20	ND
Tetrachloroethylene	10	ND
Toluene	10	22
1,2,3-Trichlorobenzene	20	ND
1,2,4-Trichlorobenzene	20	ND
1,1,1-Trichloroethane	10	ND
1,1,2-Trichloroethane	10	ND
Trichloroethylene (TCE)	10	ND
Trichlorofluoromethane	20	ND
1,2,3-Trichloropropane	20	ND
1,2,4-Trimethylbenzene	10	660
1,3,5-Trimethylbenzene	10	230
Vinyl Chloride	20	ND
o-Xylene	10	400
m + p-Xylene	20	1300
Surrogates:		
Dibromofluoromethane	123 %	
Toluene-D8	111 %	
4-Bromofluorobenzene	95.6 %	

ND - Not Detected
Concentration units = µg/L

Green Mountain Laboratories, Inc.

RR 3, Box 5210

Montpelier, Vermont 05602

Phone (802) 223-1468 Fax (802) 223-8688

GML REF. # : 1069
STATION: SB-6
ANALYSIS DATE: 07/31/96
DATE SAMPLED: 07/25/96
SAMPLE TYPE: WATER

PARAMETERS	PQL	µg/L
Benzene	1	ND
Bromobenzene	1	ND
Bromochloromethane	3	ND
Bromodichloromethane	1	ND
Bromoform	1	ND
Bromomethane	5	ND
n-Butylbenzene	2	ND
sec-Butylbenzene	1	ND
tert-Butylbenzene	2	ND
Carbon Tetrachloride	1	ND
Chlorobenzene	1	ND
Chloroethane	2	ND
Chloroform	1	ND
Chloromethane	2	ND
o-Chlorotoluene	1	ND
p-Chlorotoluene	2	ND
1,2-Dibromo-3-chloropropan	3	ND
Dibromochloromethane	2	ND
1,2-Dibromomethane (EDB)	1	ND
Dibromomethane	1	ND
o-Dichlorobenzene	1	ND
m-Dichlorobenzene	1	ND
p-Dichlorobenzene	1	ND
Dichlorodifluoromethane	2	ND
1,1-Dichloroethane	2	ND
1,2-Dichloroethane	1	ND
1,1-Dichloroethylene	1	ND
cis-1,2-Dichloroethylene	2	ND
trans-1,2-Dichloroethylene	2	ND
1,2-Dichloropropane	1	ND
1,3-Dichloropropane	1	ND
2,2-Dichloropropane	2	ND
1,1-Dichloropropene	1	ND
cis-1,3-Dichloropropene	1	ND

PARAMETERS	PQL	µg/L
trans-1,3-Dichloropropene	1	ND
Ethylbenzene	1	ND
Hexachlorobutadiene	10	ND
Isopropylbenzene	1	ND
p-Isopropyltoluene	2	ND
Methylene Chloride	5	ND
Methyl-t-butyl-ether (MTBE)	2	ND
Naphthalene	5	ND
n-Propylbenzene	1	ND
Styrene	2	ND
1,1,1,2-Tetrachloroethane	1	ND
1,1,2,2-Tetrachloroethane	2	ND
Tetrachloroethylene	1	ND
Toluene	1	ND
1,2,3-Trichlorobenzene	2	ND
1,2,4-Trichlorobenzene	2	ND
1,1,1-Trichloroethane	1	ND
1,1,2-Trichloroethane	1	ND
Trichloroethylene (TCE)	1	ND
Trichlorofluoromethane	2	ND
1,2,3-Trichloropropane	2	ND
1,2,4-Trimethylbenzene	1	ND
1,3,5-Trimethylbenzene	1	ND
Vinyl Chloride	2	ND
o-Xylene	1	ND
m+p-Xylene	2	ND
Surrogates:		
Dibromofluoromethane	123 %	
Toluene-D8	105 %	
4-Bromofluorobenzene	86.7 %	

ND - Not Detected
Concentration units = µg/L

John F. Amadon, CPSS
107 State Street
Montpelier, VT 05602
Tel. (802) 223-5946

October 20, 1996

Ms Maria Stadlmayer
Vermont Dept of Environmental Conservation
103 South Main Street
Waterbury, VT 05676

RE: VDEC Site # 96-~~2014~~ 2015 - Contaminant Identification

Dear Maria;

At the request of Mr. John Hanzas of Stone Environmental Inc (SEI), I have reviewed a chromatographic pattern of a soil sample obtained from the above referenced site in an effort to identify the primary contaminant. At first glance it was apparent to me that the contaminant is a highly weathered fuel oil. Further evaluation of the chromatographic pattern, along with a slightly better understanding of the sampling & analytical protocols, confirms that opinion.

The soil sample was obtained by SEI on 7/11/96, labeled as the 'Front Yard' and submitted to Green Mountain Laboratories (GML) where it was logged in as sample #1011 for Method 8260 Volatile Organic Analysis. Following a methanol extraction at GML, the GC/MS assay was performed on 7/17/96 and the standard 8260 report and chromatographic pattern were faxed to SEI. Enclosed is a copy of a portion of the GML Quantitation Report which includes the chromatographic pattern.

That pattern has been included in a chromatographic database that I am developing to serve as a tool for assessing various contaminated sites and/or monitoring remedial impacts. Another use of that database is in helping to identify contaminants. Enclosed as Figure 1 is one type of comparison with the top pattern being the one in question and the bottom pattern being a biodegraded gasoline pattern lacking B, T, & E, but demonstrating xylenes and the other alkylated benzenes typical of a gasoline contaminant. Gasoline patterns, for these volatile organic type analyses (8020, 8240, 8260) do not demonstrate the 'bulge & spikes' observed in the top pattern. The shape and retention time window for that 'bulge & spikes' are characteristic of a fuel oil. The degree of 'spikeiness', or in this case, the general lack of tall spikes, provides an indication of the degree of weathering and/or biodegradation.

I have also enclosed a copy of a recent article from the Journal of Environmental Quality (JEQ) summarizing some work done on landfarming of fuel oil contaminants in France. Of primary importance here, are some of the chromatographic patterns which vividly demonstrate the 'bulge & spike' concept. Please note, however, that the analytical procedures between the French work and our 8260 type assays are not the same although the

principles and separations are comparable. In general, the taller n-alkane (or saturate) spikes do degrade more rapidly than the aromatics (alkylated benzenes) or PAHs (polycyclic aromatics). On other 8260 type chromatographic patterns that I have reviewed over the years, I have observed the true 'spike' pattern for 'fresh' or new fuel oil contamination.

In referring back to Figure 1, there are several other points I would like to make. Both patterns have dashed green lines identifying those chromatographic peaks utilized as internal standards and/or surrogates for analytical quality control. The height/area (relative abundance) of peaks is proportional to concentration. The top fuel oil pattern has significantly higher peaks than the standards/surrogates. This indicates the fuel oil concentration was very high. In fact, the GML analyst distinctly remembers this sample due to both its strong fuel oil odor and the need to thoroughly clean and 'bake' the GC column.

A second point concerning Figure 1 is the presence and relative heights of the peaks within the 10 to 20 minute time window. These peaks, which were not components of the 8260 target list, are probable intermediary metabolites of the natural biodegradation or weathering that is occurring at both sites.

A final point concerns the usefulness of such patterns. As I alluded to earlier, a database has been started to allow for chromatographic comparisons between samples. Each chromatogram can be digitized as a layer within a standardized format. Overlays or other types of comparisons, such as Figure 1, can than be used as tools in site/remediation assessments.

I trust this explanation and enclosures have served to help justify my opinion that the contaminant of concern at Site # 96-2014 is indeed a weathered fuel oil. Please feel free to contact me with any further comments or questions you may have on this particular site or chromatographic interpretations in general.

Respectfully submitted;

John Amadon, CPSS

enclosures:
cc: John Hanzas, SEI

Quantitation Report

Data File : C:\HPCHEM\1\DATA\011.D
Acq On : 17 Jul 96 11:54 am
Sample : 1011 07/11/96 FRONT YARD
Misc : 10
Quant Time: Jul 17 14:21 1996

Vial: 3
Operator: BD
Inst : 5972 - In
Multiplr: 1.00

Method : C:\HPCHEM\1\METHODS\ALTHEA.M
Title : 8260
Last Update : Wed Jul 17 13:54:49 1996
Response via : Multiple Level Calibration

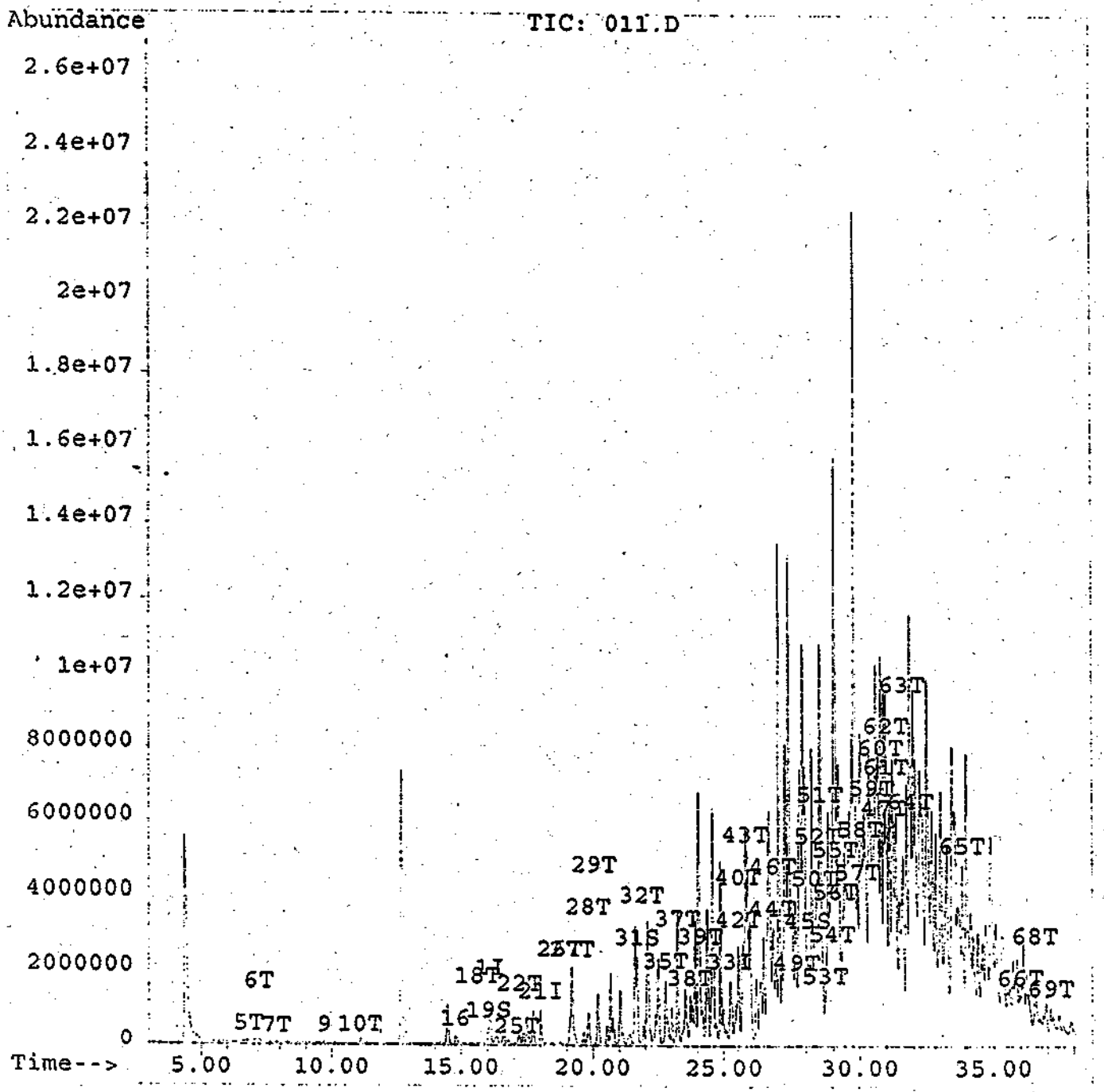
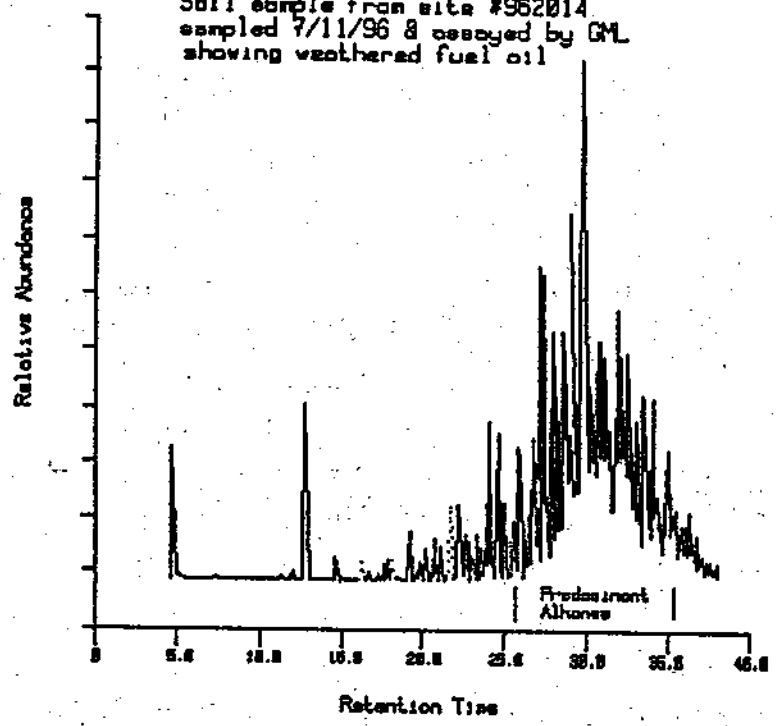
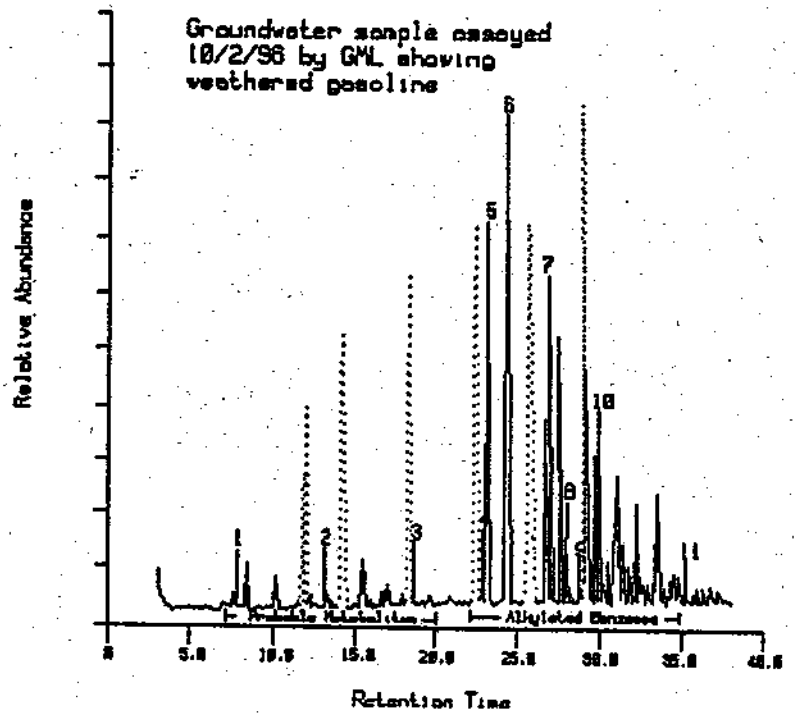


Figure 1





KEY

- Weathered Fuel Oil
- Weathered Gasoline
- ····· Internal Standards/Surrogates

1 MTBE
2 Benzene
3 Toluene
4 Ethylbenzene
5 m & p Xylenes
6 o Xylenes
7 1,3,5 - Trimethylbenzene
8 1,2,4 - Trimethylbenzene
9 Isopropyltoluene
10 n Butylbenzene
11 Napthalene

Method 8260 Chromatographic Patterns		
scale: as shown	Date: 10/28/96	Drawn by: JFA

Land Treatment of Oil-Based Drill Cuttings in an Agricultural Soil

C. H. Chaineau, J. L. Morel, and J. Oudot*

ABSTRACT

The biodegradation, mobility, and phytotoxicity of fuel oil hydrocarbons (HC) contained in drill cuttings (DC) were investigated in a 28-mo field experiment. In an agricultural soil, three plots were treated with DC on an extensive basis: 15, 30, and 60 Mg DC ha^{-1} corresponding to 1.5, 3, and 6 Mg HC ha^{-1}. Concentration and chemical composition of residual HC in the soil profile (0–80 cm) were periodically determined. The decrease in HC concentration was proportional to the loading rates and mainly due to microbial biodegradation. Gas chromatographic analyses demonstrated the metabolism of n- and branched alkanes and of GC-resolved aromatics. The persistence of some polycyclic saturates and aromatics was shown. At the end of the experiment, 10% of the initial HC amount persisted in the surface soil. A vertical selective migration of the lightest HC was shown during the first days and a low leaching of HC and metabolic byproducts toward the subsurface soil and drainage water occurred. The soil treatment modified the soil fertility: pH and Ca increased due to drill cuttings addition while P_2O_5 and K_2O decreased. Crops (maize [*Zea mays* L.], wheat [*Triticum aestivum* L.], pea [*Pisum sativum* L.]) were successively cultivated and harvested. Phytotoxicity, resulting in significant reductions of yields was observed on the two first crops on the most heavily treated plots, but no uptake of HC in the seeds was measured.

THE TREATMENT of oil-based wastes is a major problem in petroleum industry. For instance, onshore and offshore drilling operations generate oily wastes like the drill cuttings (DC) that are composed of the oil-based drilling fluid mixed with subsoil material (mineral matter). These products are pollutants of water and land when discharged without appropriate treatment. In most cases, they are disposed of by a variety of methods such as incineration and controlled dumping. The landfarming or land treatment of oily wastes has been used by the petroleum industry (Cansfield and Racz, 1978; Morgan and Watkinson, 1989) since it has been recognized that hydrocarbons (HC) can be metabolized by the indigenous microbial population of the soil (Bossert and Bartha, 1984; Oudot et al., 1989; Raymond, 1976). Numerous wells are drilled in agricultural areas, so the landfarming of DC may represent an alternative way for treating HC contained in DC. The biodegradation of drill cutting hydrocarbons has been studied in soil microcosms (Chaîneau et al., 1995). However, the fate and effects of DC (biodegradation, abiotic losses, plant production) have not yet been investigated in the field.

With high inputs of oily wastes (>50 Mg HC ha^{-1}), growth of vegetation is totally inhibited for a long period due to HC phytotoxicity (Amakiri and Onofeghara, 1983; Baker, 1970; Kinako, 1981; Terje, 1984). In this study, land treatment was realized on an extensive basis, i.e., HC loading rates were deliberately low enough to permit normal plant cultivation.

A 28-mo field experiment was set up following a petroleum drilling operation. Resulting DC were spread on the soil at three different loading rates near the production site. The loading rates were 1.5 to 6 Mg HC ha^{-1}, which is about 10 times lower than usually applied (Prantera et al., 1991; Rangel et al., 1988; Zimmerman and Robert, 1991). Maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and pea (*Pisum sativum* L.) were successively cultivated on the DC-treated plots. The biodegradation rate and extent and leaching of HC were determined and the effects of mineral and organic components of DC on crops productivity and soil chemistry were studied. Possible uptake of HC in the aerial parts of the plants was also monitored.

MATERIALS AND METHODS

Drill Cuttings

In February 1992, 75 Mg of drill cuttings were produced during drilling operations at Montmirail, Marne, France. The drilling fluid used was composed of 66% fuel oil, 22% water, 1.3% emulsifier, 1.7% filtrate reducing agent (V/V), and 6% $CaCl_2$, 3% $Ca(OH)_2$ (W/W). The resulting DC exhibited a sandy texture, were alkaline ($9 < pH < 10.1$), contained an average of 10% fuel oil and a high amount of Ca (Table 1). No significant amount of heavy metals was measured in the DC. The fuel oil was composed of 60% saturates, 30% aromatics, and 10% resins (Chaîneau et al., 1995).

Experimental Plots, Landfarming Operations, and Cultivation Procedures

Four plots were layed out on an agricultural elluviated brown soil (Typic Hapludalf) near the drilling site. Characteristics of the Ap horizon were a silty-clay texture, a pH of 7.1, and a rather high amount in P (Table 1). In April 1992, DC were spread on three plots: L (low, 0.86 ha), M (medium, 0.62 ha), and H (high, 0.72 ha), respectively, at 15, 30, and 60 Mg DC ha^{-1} with an agricultural spreader, which corresponded to loading rates of 150, 300, and 600 g fuel oil HC m^{-2}. A control plot T (0.86 ha) was left untreated. A drainage system buried at 60 cm allowed for the collection of leachate respectively in the control and in M + H plots. Plots were immediately plowed and harrowed after DC spreading, and cultivated according to standard agricultural practices during three growing seasons. Maize (var. DK 250) was sown 3 d after DC spreading. Fertilization, providing 140 kg N ha^{-1}, 140 kg P_2O_5 ha^{-1}, and 140 kg K_2O ha^{-1} was applied a week later. Maize was harvested in October 1992 and after plowing and harrowing, the field was sown with wheat (var. THESEE). Fertilization was 120

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Abbreviations: HC, hydrocarbon; DC, drill cutting; Mg, megagram; GC, gas chromatography; TOC, total organic carbon; CEOM, chloroform-extractable organic matter; THB, total heterotrophic bacteria; HUB, hydrocarbon utilizing bacteria; MPN, most probable number; CPI, carbon preference index; PR, pristane; PH, phytane; UCM, unresolved complex mixture; PAH, polycyclic aromatic hydrocarbon.

kg P_2O_5 and 120 kg K_2O ha^{-1} in October 1992 and 200 kg N ha^{-1} in February 1993. Wheat was harvested in August 1993 and the soil remained uncultivated until April 1994. At that time the field was plowed and harrowed, and pea (var. SOLARA) was sown and fertilized with 120 kg P_2O_5 and 120 kg K_2O ha^{-1}. Pea was harvested in August 1994. The density, plant height, and grain yield of each crop were measured in all four plots and statistically analyzed by analysis of variance ANOVA. Saturated and aromatic HC were analyzed in the seeds of the plants when harvested.

Soil and Water Sampling

Soil samples were collected with a 5-cm diameter corer 3 d and 1, 2, 6, 12, 18, and 24 mo following spreading. In each plot, five individual samples were taken in the 0- to 20-, 20- to 40-, 40- to 60-, and 60- to 80-cm layers and kept frozen until HC analyses. Samples of drainage water were collected periodically with two automatic portable samplers (Streamline 800 SL, American Sigma) during rainy periods. In addition, the flow of drainage water was continuously measured with an automatic portable computer linked to a flow sensor (SAB 600, CR2M). The water samples collected in glass bottles were kept at 2°C until HC and total organic carbon (TOC) analyses.

Chemical Analyses

Soil and seed samples (70 g) were dried for 12 h at 60°C and Soxhlet extracted with chloroform for 8 h. Hydrocarbons were extracted from the leachate water with 30 mL of chloroform per liter of water in separatory funnels. In both cases, extraction efficiency was greater than 95%, even on the aged samples (Chaineau et al., 1995). The chloroform extract was purified by percolating on a 60- to 100-mesh Florisil column that retained most biogenic polar compounds. Filtered samples were evaporated in a preweighed dish. The florisil-purified chloroform-extractable organic matter (CEOM), including HC and some polar biogenic lipids, was weighed and analyzed by computerized capillary gas chromatography (GC). The Delsi DI 200 chromatograph was equipped with a direct injection port and a FID detector set at 350°C; carrier gas was helium under 0.08 MPa (0.8 bar); the column was a CP Sil 5 CB (Chrompack) capillary column (50 m by 0.32 mm, film thickness 0.25 μm); temperature programming was 100 to 320°C, 3°C min^{-1}. Acquisition and further numerical treatment of data were performed using custom-made computer programs. In some cases, the total extract was separated in saturated, aromatic, and polar fractions by successive elution with hexane, benzene, and methanol on an activated silica-gel column (Chaineau et al., 1995). The GC-resolved compounds of the saturated and aromatic fractions were identified on reference analyses by gas chromatography–mass spectrometry using the same chromatographic conditions and an ITD 800 (Finnigan MAT) mass detector.

The TOC was measured in soil and water samples to determine whether hydrocarbons and/or metabolic by-products were carried away in the drainage system during rains. The TOC was determined by infrared detection of CO_2 after combustion (DC 80 Dohrmann Xertex analyzer). pH, CaO, N (total, NO_3, NH_4), P (P_2O_5 Olsen), and K (K_2O) were periodically analyzed in surface soil samples (0–20 cm) according to AFNOR standard methods.

Table 1. Composition of drill cuttings and agricultural soil (0–20 cm).

	Drill cuttings	Soil
pH	9.1	7.1
Silt %	20	52
Clay %	10	29
Sand %	70	19
Organic matter %	12.4	1.8
Total N %	0.6	1.2
C/N	103	8.4
P_2O_5 % (Olsen)	0.19	0.15
Total Ca %	11	0.3
Fuel oil %	10	0

Bacterial Counts

In control and H plots, the numbers of total heterotrophic bacteria (THB) and hydrocarbon utilizing bacteria (HUB) were periodically determined with the most probable number method (MPN). An average sample was prepared by homogenizing aliquots of five individual topsoil (0–20 cm) samples. For THB three tubes of trypcase-soy (30 g L^{-1}) medium (Bio-Mérieux) were inoculated with decimal dilutions of soil. The tubes were incubated at 24 ± 1°C for 3 d and the number of viable microorganisms was obtained from standard MacCrady tables after examination of growth-positive tubes. The number of HUB was determined by the same MPN technique, three tubes per dilution. The mineral medium was composed of 0.68 g L^{-1} KH_2PO_4, 1.79 g L^{-1} Na_2HPO_4, 0.35 g L^{-1} $MgSO_4$, 1 g L^{-1} NO_3NH_4, $CaCl_2$, 0.4 mg L^{-1} $FeSO_4$, and 0.1 mL L^{-1} of a solution that contained 100 mg L^{-1} of H_3BO_4, $MnSO_4$, $ZnSO_4$, $CuSO_4$, and $CoCl_2$. After sterilization, 0.1 mL of sterile crude oil was added to each tube. Inoculated tubes were incubated for 21 d at 24 ± 1°C.

RESULTS

Hydrocarbon Weathering in Soil

A chromatogram of the initial composition of the fuel oil extracted from DC as determined by computerized capillary gas-chromatography is shown in Fig. 1. In the control plot, CEOM contained 10% biogenic HC and 90% biogenic polar compounds not retained on Florisil. Identified hydrocarbons were essentially odd n-alkanes in the nC27–nC33 range with a carbon preference index (CPI), i.e., ratio Σ odd n-alkanes/Σ even alkanes of 10 (Fig. 1). The major part of these biogenic hydrocarbons was located in the 0- to 40-cm surface layer with amounts of CEOM ranging from 50 to 100 mg kg^{-1}. A lower amount of CEOM (10–50 mg kg^{-1}) was detected in the 40- to 60- and 60- to 80-cm layers.

The HC concentrations over time in the four plots are shown in Fig. 2 (logarithmic scale). The amounts of fuel oil HC were calculated as CEOM in treated soils minus CEOM in control soil. Three days after DC spreading, the concentration decreased with depth from 500 (L) to 2200 mg kg^{-1} (H) in the 0- to 20-cm layer to 30 (L) to 1000 (H) mg kg^{-1} in the 60- to 80-cm layer. At the same time, GC analyses (Fig. 3) revealed that only the lightest fraction of the fuel oil (nC13–nC19) had migrated down to the 40- to 80-cm layer. Compounds below nC13 were lost by evaporation on the site and during analytical processing of the sample. Later, all HC in the nC15–nC27 range were detected by GC in all layers in the same

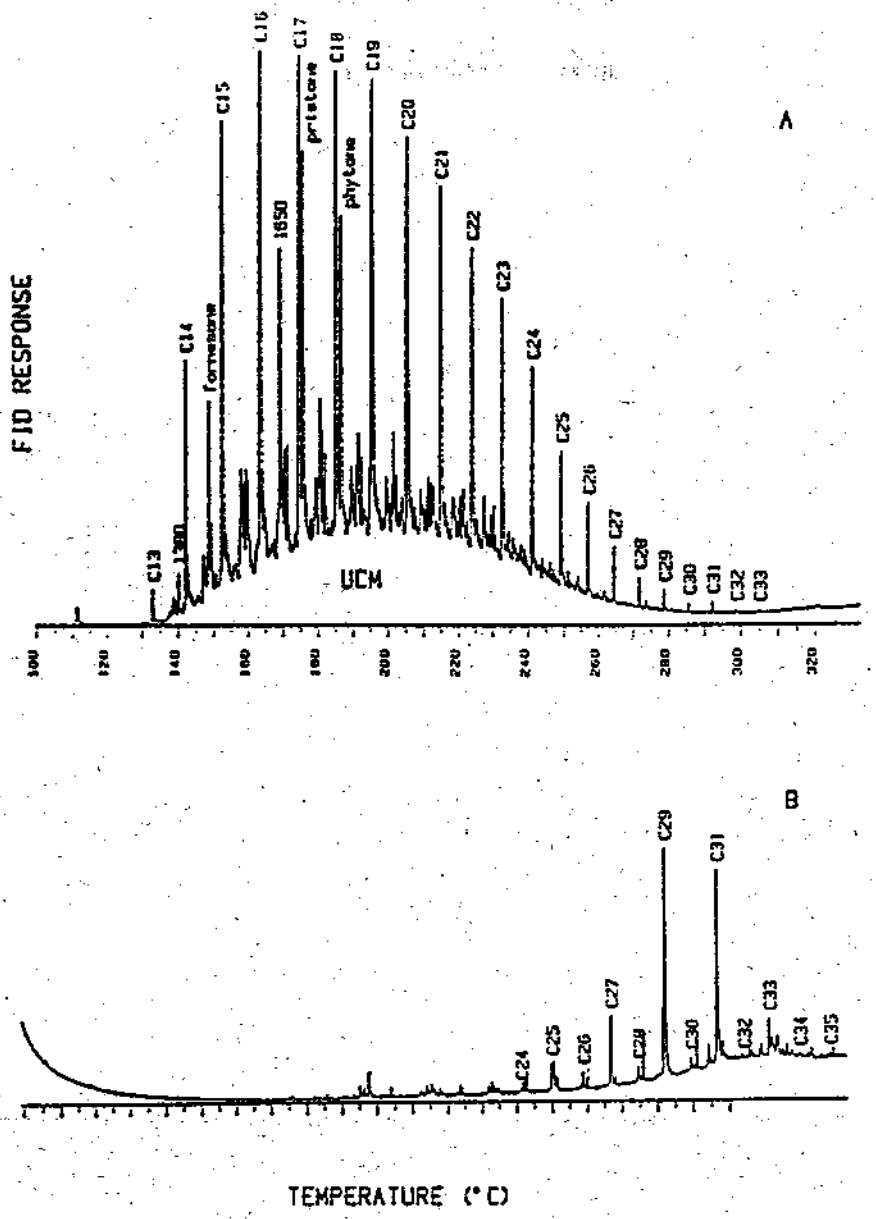

Fig. 1. Gas chromatographic analysis of fuel oil hydrocarbons extracted from (*A*) drill cuttings and (*B*) biogenic hydrocarbons extracted from control soil. The numbers represent the carbon numbers of n-alkanes. Intermediate peaks are branched alkanes and GC-resolved aromatic compounds. UCM, unresolved complex mixture.

relative amounts as in the initial oil. During the rest of the experiment, the major part of the fuel oil remained located in the 0- to 40-cm subsurface soil (from 200 to 1000 mg kg^{-1} after 1 mo, Fig. 2); in this layer, the concentration decreased regularly with time (70–210 mg kg^{-1} after 2 yr). Decreasing amounts of fuel oil (from an average of 80 mg kg^{-1} after 1 mo to <5 mg kg^{-1} after 2 yr) were detected in the deeper 60- to 80-cm horizon.

The GC analyses showed the disappearance of fuel oil HC (Fig. 4). Normal and branched alkanes as well as GC-resolved aromatic HC decreased regularly and were quite completely removed between 7 and 12 mo. The ratios C17/pristane (PR), C18/phytane (PH), and sum of resolved peaks to unresolved complex mixture (UCM) decreased as exposed in Table 2. Isoprenoids PR and PH resisted until 1 yr but were finally almost totally degraded. After 2 yr, remaining n- and branched alkanes from the fuel (nC16–nC28) were at the same or lower concentration than biogenic hydrocarbons (nC29–nC33), in the order of 0.5 mg kg^{-1} for each compound. Figure 5 indicates that most GC-resolved aromatics were eliminated after 2 yr. Undegraded HC were included in the UCM of the chromatograms. The total remaining UCM was composed of 2/3 saturates and 1/3 polycyclic aromatics (PAHs) including essentially di- and triaromatics. Initial UCM of undegraded fuel oil contained the same relative amount of saturated and aromatic HC (2/3, 1/3), which indicates that both classes of HC were eliminated to almost the same extent (Chaineau et al., 1995). Similar qualitative chromatograms were obtained in the three treated plots, in all sampled soil layers.

By integrating HC concentrations over the 0- to 80-cm soil layer, the total amount of HC (g m^{-2}) was calculated in each plot. Figure 6 reports the global weathering of

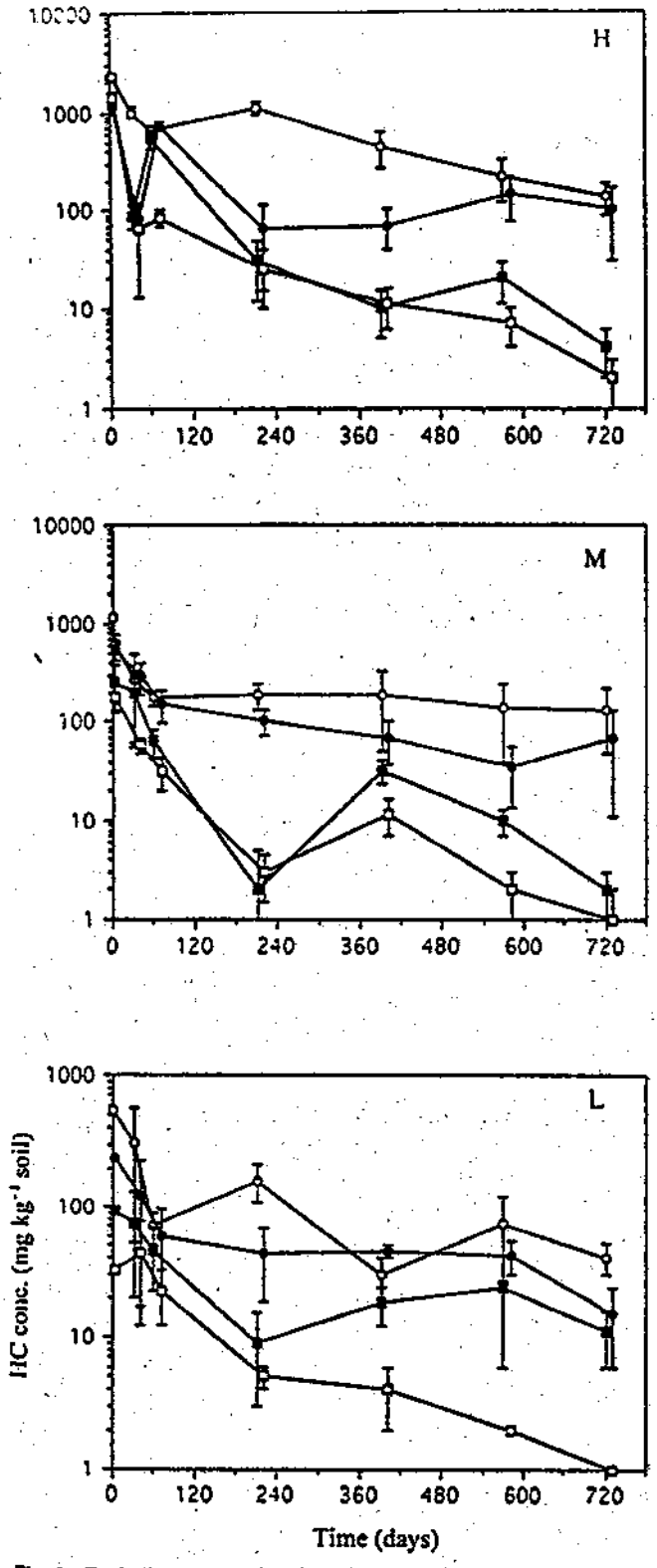

Fig. 2. Fuel oil concentration (logarithmic scale) in the 0- to 20- (○), 20- to 40- (●), 40- to 60- (■), and 60- to 80- (□) cm soil layers of the plots treated with 15 Mg (L), 30 Mg (M), and 60 Mg (H) drill cuttings per hectare.

HC during the 2-yr period (linear scale). The decrease with time was regular in all plots, and the rate of loss was higher in the beginning than in the late part of the experiment. After 2 yr, total losses were respectively 93, 88, and 91% of the initial amount in L, M, and H plots.

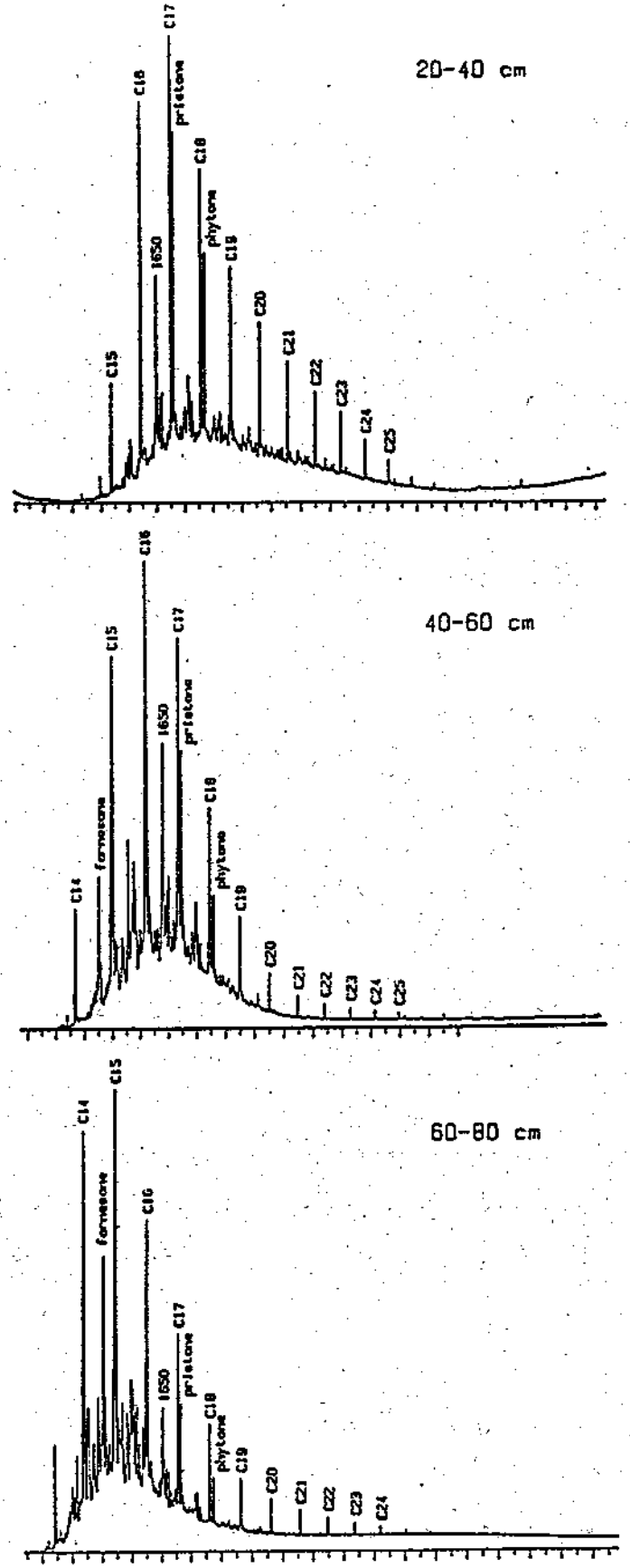

Fig. 3. Chromatograms at Day 3 show selective migration of the light HC of the DC in the soil profile. See Fig. 1 for fuel oil composition in the 0- to 20-cm surface layer.

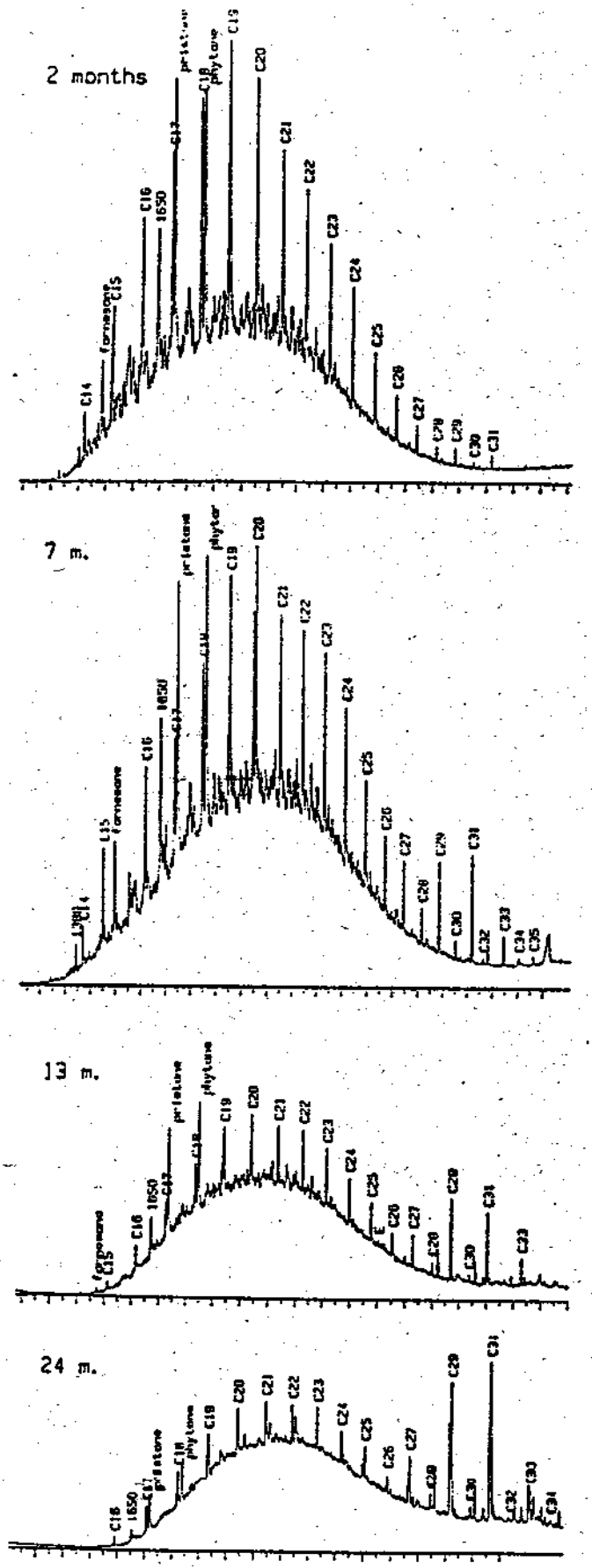

Fig. 4. Gas-chromatographic analyses of soil extracts over time show biodegradation of fuel oil HC in the 0- to 20-cm layer of H plot. See Fig. 1 for initial composition.

Table 2. Chromatographic ratios indicating biodegradation of HC in the 0- to 20-cm layer of H plot.

Ratios	Initial	8 d	60 d	210 d
C17/pristane	1.52	0.78	0.68	0.53
C18/phytane	1.69	0.85	0.69	0.52
peaks/UCM†	0.46	0.16	0.10	0.08

† Ratio sum of GC-resolved peaks/UCM.

Leaching Waters

Air temperature, rainfall, and TOC concentration in the drainage water are reported on Fig. 7. No significant difference in TOC between control and M + H plots was observed during the first 3 mo but GC analyses demonstrated the presence of fuel HC in treated plots (≈1 mg HC L^{-1}) 5 d after spreading. This leaching of fuel HC lasted for about 1 wk and then stopped. The HC were also present in drainage water after summer storms in 1992. During the two winter seasons, TOC in the treated plots was 2 to 6 times higher (2–20 mg L^{-1}) than in control (1–12 mg L^{-1}). The HC concentration in treated plots water was about 1 mg HC L^{-1}. By integrating TOC in treated plots minus TOC in control relatively to drainage water flow and drainage system efficiency over the whole experiment, it was calculated that the amount of excess soluble organic carbon was in the range of 7 g m^{-2} in H and 3.5 g m^{-2} in M.

Bacterial Counts in Control and Plot H

Figure 8 shows the changes in microbial populations (THB, HUB) in the Ap horizon (0–20 cm) of control and plot H. Soil cultivation (tilling, fertilization) modified only slightly the number of bacteria in the control. The ratio HUB/THB remained quite constant, around 1%.

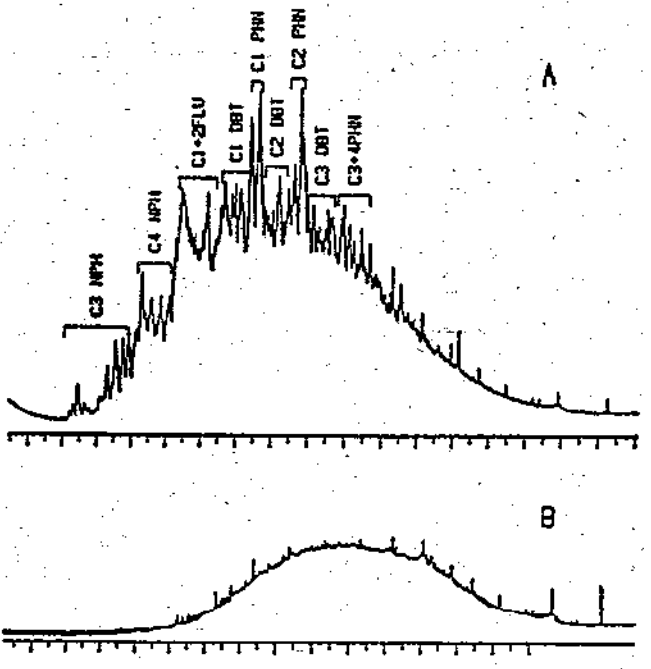

Fig. 5. Analyses by GC-MS of the aromatic fraction of HC contained in (*A*) DC and in (*B*) the 0- to 20-cm layer of H plot after 24 mo show the biodegradation of GC-resolved PAHs. NPH, naphthalenes; FLU, fluorenes; DBT, dibenzothiophenes; PHN, phenanthrenes; C1–C4, number of alkyl substitutions.

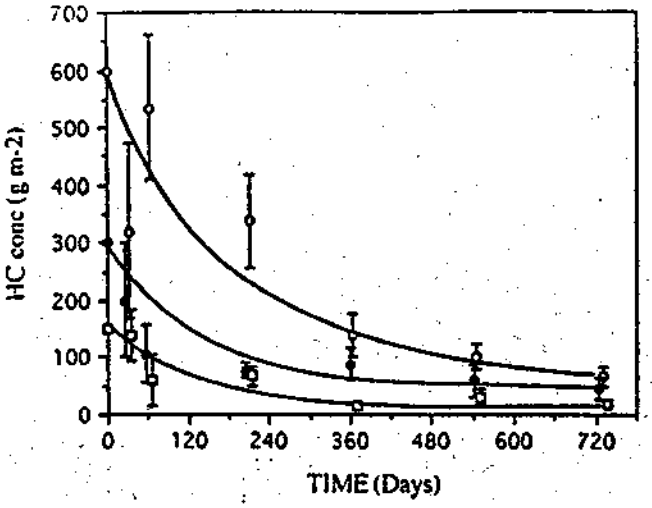

Fig. 6. HC concentration in soil (linear scale) vs. time in plots H (○), M (●), and L (□), integrated over the 0- to 80-cm soil profile.

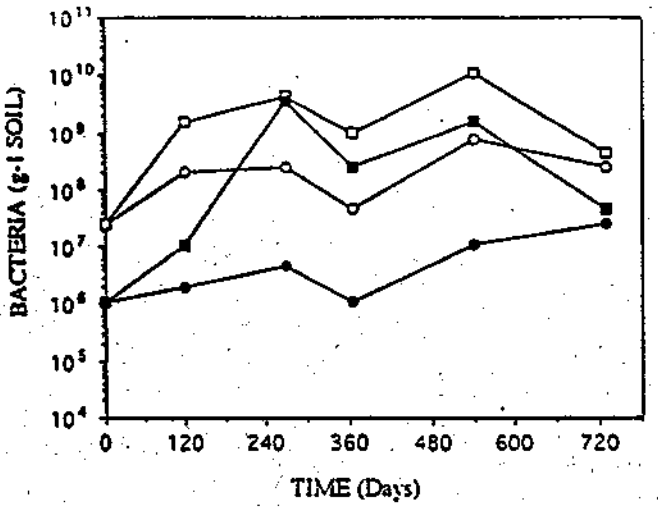

Fig. 8. Changes in bacterial populations over time in DC-treated (H) and control soils 0- to 20-cm layers: (□) total heterotrophic bacteria THB in H, (○) THB in control, (■) hydrocarbon utilizing bacteria HUB in H, (●) HUB in control.

By contrast, the addition of drill cuttings strongly increased the numbers of viable microorganisms. After 8 mo, a 1000-fold increase in the HUB population and a 20-fold increase in the THB population, compared with the control, were observed. Up to 90% of the bacteria were adapted to HC assimilation in H. The HUB and THB decreased regularly 18 mo after the soil treatment. At the end of the experiment, HUB and THB in H had returned to levels similar to control.

Plant Growth and Hydrocarbons in Seeds

During the growth of maize, visual effects of the application of DC were recorded. Seedling emergence and plant density were not affected by DC application (Table 3). On the most heavily treated plots (M, H), maize exhibited symptoms of P deficiency at the 3 to 4 leaves stage as indicated by the reddening of leaves.

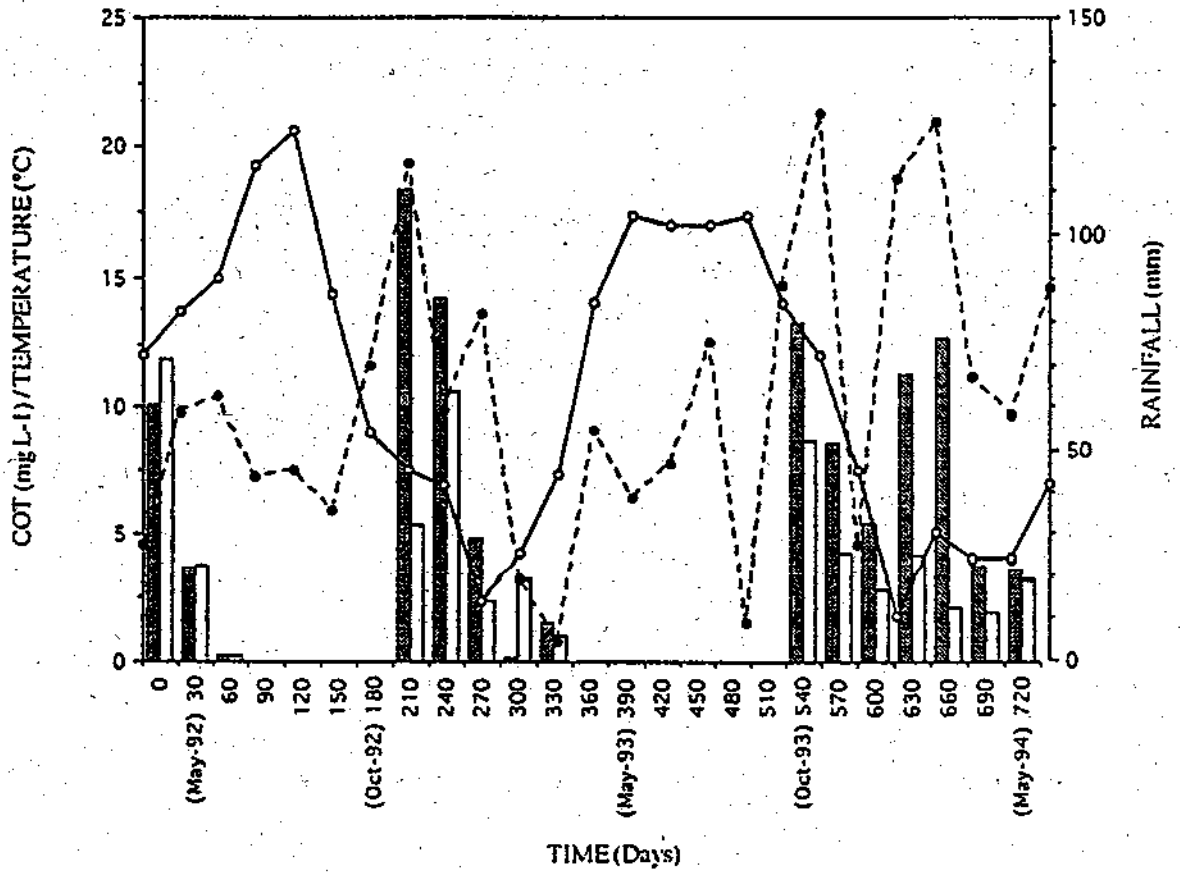

Fig. 7. Monthly measurements of air temperature (○), rainfall (●), and TOC in the drainage water from control plot (□) and H + M treated plots (▨) during the 2-yr experiment.

Table 3. Effect of drill cuttings on mature plants.

Plant	Control	L	M	H
		Density (plants m^{-2})		
Corn	10.3	10.1	10.3	10.1
Wheat	311	307	323.5	297.5
Pea	95	86	94	88
		Height (cm)		
Corn	237	235	228	215
Wheat	83	77	73.6	74.5
Pea	61.5	64	69	60.7
		Yield (Mg ha^{-1})		
Corn	8.87	8.25	8.58	7.33
Wheat	7.57	6.94	6.56	6.47
Pea	5.31	5.10	5.36	5.64

Drill cuttings affected the physiology of the plant: the average number of leaves per plant was lower, and plant height was reduced in the treated plots relative to the control. In addition, the flowering was delayed by 5 d compared with the control. The grain yields were statistically significantly reduced by 17% on H and 7% on M. In plot L, a nonsignificant reduction in plant growth was observed. Wheat height was also slightly reduced on the treated plots, but no deficiency symptoms were noted during the growing period. Nevertheless, yields were still significantly reduced on H (−16%) and M (−8%). After 2 yr, pea was not affected by the occurrence of remaining fuel oil HC in the soil and the yield was comparable to the control. The GC analyses showed that no fuel saturated or aromatic HC were detectable in the seeds of the three crops. Only biogenic n-alkanes in the nC21–nC27 range for maize, nC21–nC33 for wheat, and nC21–nC31 for pea were detected.

Table 4. Chemical analyses of the 0- to 20-cm surface soils.

		Time (days)				
		3	90	365	540	720
pH	Control	7	6.8	6.5	6.8	6.7
	L	6.8	6.6	7.1	6.8	7.1
	M	7	6.6	7.4	7.5	7.4
	H	7	7.2	7.7	7.9	7.9
CaO (%)	Control	3.33	3.25	3.44	3.23	2.65
	L	3.35	2.93	3.44	2.86	3.13
	M	3.36	3.34	3.88	4.16	3.66
	H	5.72	4.9	7.03	7.26	7.52
Mineral N (%)	Control	0.06	0.07	0.02	0.01	0.03
	L	0.07	0.06	0.05	0.01	0.02
	M	0.06	0.09	0.02	0.01	0.03
	H	0.05	0.08	0.04	0.01	0.02
Total N (%)	Control	1	1.1	1	1	1
	L	0.9	0.9	1	1	1
	M	1	1	1.1	1.1	0.9
	H	0.9	1	1.1	1	0.9
P_2O_5 (%) (Olsen)	Control	0.16	0.13	0.11	0.14	0.17
	L	0.10	0.11	0.55	0.11	0.06
	M	0.07	0.13	0.11	0.08	0.11
	H	0.06	0.08	0.08	0.07	0.11
K_2O (%)	Control	0.21	0.13	0.11	0.14	0.17
	L	0.21	0.11	0.06	0.11	0.16
	M	0.22	0.13	0.11	0.08	0.11
	H	0.24	0.08	0.08	0.07	0.11
Organic C (%)	Control	8	9.2	8.9	9.6	8.3
	L	8.3	8.7	8.9	10.4	8.1
	M	9.1	9.6	10.7	10.4	10
	H	9.7	9.9	10.2	11	9.9

Soil Fertility

The DC soil treatment modified the agronomic soil parameters of the Ap horizon (Table 4). Plot H was the most affected: pH, CaO, and TOC increased immediately after spreading. Phosphorus and exchangeable K were always lower in treated plots than in the control. The reduction in available P was concomitant with the increase in pH. Total and mineral N were not affected by the addition of drill cuttings to the soil.

DISCUSSION

Biological Removal of Drill Cutting Hydrocarbons from Soil

This study showed that the bulk of drill cutting hydrocarbons can be biodegraded by the microbial population of an agricultural soil. In all plots, the chromatograms were typical of petroleum products that have undergone microbial degradation. The GC analyses showed that n- and branched alkanes were first assimilated (<6 mo). Isoprenoids pristane and phytane resisted until 6 mo but were finally degraded. The GC-resolved aromatics were almost totally degraded. A persistence of the UCM was noted. These results are in agreement with what was already observed in the biodegradation of HC in experimental cultures (Chaineau et al., 1995; Oudot, 1984; Pritchard et al., 1976), in previous landfarming experiments (Bossert et al., 1984; Oudot et al., 1989), or in bioremediation studies (Atlas, 1991; Phelps et al., 1994; Wang et al., 1990).

It should be pointed out that the degradation of drill cutting HC was not complete; resistant HC (10% of the initial load of each plot) persisted as part of the stable organic matter of the soil. These recalcitrant compounds constitute the typical UCM of biodegraded petroleum products. They are mainly composed of polycyclic alkylated saturated and aromatic HC (Killops and Al-Juboori, 1990; Leahy and Colwell, 1990; Oudot, 1984) and T-shaped molecules (Gough and Rowland, 1990). The long-term ecological impact of such compounds is largely unknown; attention should be paid to the persistence of potentially carcinogenic PAHs. The extent of biodegradation was similar to what was observed in the laboratory experiment (Chaineau et al., 1995).

Biogenic HC and traces of fuel n-alkanes were not degraded in the treated plots during the experiment, though in liquid culture media, n-alkanes are completely biodegraded by bacteria and fungi (Fedorak and Westlake, 1981; Oudot et al., 1987; Pritchard et al., 1976). This indicates that part of the HC are protected from biodegradation, most likely because they are bound to DC or to the organo-mineral matrix of the soil in a way that prevents accessibility for microorganisms (Robinson and Novak, 1994; Kowalska et al., 1994; Chaineau et al., 1995).

The HC degradation occurred in the entire soil profile (0–80 cm), though other studies showed a biodegradation only in the upper 0- to 30-cm layer of the soil where oxygen transfer is sufficient to sustain microbial activity (Oudot et al., 1989). The drainage system may have

provided the soil with an enhanced aeration. Microbial counts showed that aerobic HC-degrading bacteria were numerous (10^5–10^6 cell per gram) even in the 60- to 80-cm layer.

By integrating over the 0- to 80-cm soil profile, the biodegradation rates (expressed in HC amounts) throughout the experiment in the plots L, M, and H were 6, 11, and 23 g m^{-2} mo^{-1}, respectively. These rates were higher during the first year (12, 20, and 37 g m^{-2} mo^{-1}) than during the second (2, 4, and 10 g m^{-2} mo^{-1}). The biodegradation rates were proportional to the loading rates and were rather low compared with what has been reported for biodegradation rates of petroleum compounds in other landfarming experiments (Bossert and Bartha, 1984; Morgan and Watkinson, 1989; Oudot et al., 1989), or in bioremediation treatment of polluted soils (Atlas, 1991; Pollard et al., 1994). However, when expressed in percent of initial weight, biodegradation rates were as fast as usually observed in HC biodegradation in the field, i.e., about 50% was degraded in the first year and about 50% of the remaining compounds were degraded in the second year.

During the first year, mineral N fertilization introduced 14 g N m^{-2}, which could support a theoretical biodegradation of about 140 g HC m^{-2} (C/N = 10; Bossert and Bartha, 1984). In the absence of plant development this amount would have been sufficient for L but limiting for M and H. In fact, even with maize growth, no inhibition of biodegradation was recorded, suggesting that HC-degrading microorganisms used also the soil organic N, as already observed (Fusey et al., 1983; Song et al., 1990). With the low HC loading rates that were applied, mineral fertilization used for plant cultivation was adequate for HC biodegradation and plant growth. Phosphorus and K were also introduced in sufficient amounts for microbial degradation by fertilization (Mills and Frankenberger, 1994). During the experiment, the temperature was typical of temperate zones and was lower than the optimal temperature for biodegradation of HC (Atlas, 1991). In the laboratory, biodegradation of the same fuel oil in the same soil was five times faster (Chaîneau et al., 1995), but in this case, aeration, nutrients, and temperature were held at optimum levels. Temperature may have been the most limiting factor, since mean temperature was 11°C in the field and 24°C in the laboratory.

It has been previously noted that the rhizosphere of plants has a favorable effect on the biodegradation of pesticides (Anderson et al., 1994) and hydrocarbons (Aprill and Sims, 1990; Chaîneau, 1995). In the absence of plots without plant cover, the effect of crops cannot be assessed, their presence may have favored HC removal.

Microbiological Aspects

In general, a strong increase in numbers of bacteria is observed after an oil treatment (Llanos and Kjoller, 1976; Song and Bartha, 1990). Experiments conducted on these DC under controlled conditions have shown a rapid adaptation of the soil microbiota to degradation of HC (Chaîneau et al., 1995), and a high specific diversity of microorganisms is involved in the biodegradation, including several genera of bacteria and fungi (Chaîneau et al., 1995). In the field experiment, HUB in soil of plot H increased sharply from 10^6 to 3.10^9 viable cells and up to 90% of the bacterial population was able to degrade HC. However, adaptation was slower than in laboratory conditions (6 mo vs. 15 d). Numbers of bacteria declined as most of the easily degradable compounds were eliminated and only recalcitrant cyclic compounds remained.

Selective Migration of Light Hydrocarbons

In this field experiment, the main part of the HC remained trapped in the 0- to 40-cm layer of the soil. However, HC were detected in the entire soil column as soon as 3 d after spreading. The GC analyses demonstrated selective migration of the lightest compounds of the fuel. Such selective vertical infiltration has not previously been documented in agricultural soil but was already observed in a lysimeter experiment (Oudot et al., 1989) and in polluted soils (Oudot, 1989). The fast vertical migration of light HC (nC13–nC18) was probably due to the chromatographic properties of clays (Leythaeuser et al., 1983). This selective infiltration lasted less than 8 d. After that time, the whole chromatographic spectrum (nC14–nC27) was detected in the 40- to 80-cm layer, indicating that subsequent vertical migration concerned progressively the total fuel oil.

Abiotic Losses of Drill Cutting Hydrocarbons

Laboratory studies showed that microbial degradation can eliminate 75% of this fuel oil (Chaîneau et al., 1995) when total loss in the 0- to 80-cm layer was 90%. This indicates that other abiotic mechanisms occurred. By comparison of HC concentrations in the 40- to 80-cm layer in the control and treated plots it can be shown that the vertical flow ranged from 6 μg HC g^{-1} d^{-1} during the first 8 d to <1 μg HC g^{-1} d^{-1} after 1 yr. It was negligible during the second year. It could be thought that such a flow is extremely low, but when integrating over 1 yr it appears that 8% of the initial HC load has migrated deeper than 80 cm. The total depth of the migration is not known. Assuming an average resulting concentration of 20 mg kg^{-1}, infiltration in H could have reached a depth over 2 m. Infiltration is proportional to initial HC amounts and is related to the soil structure and climatic conditions (Chaîneau, 1995). It has been shown that high loading rates result in a deep infiltration that can eventually reach ground waters (Morgan and Watkinson, 1989). This occurs in the case of accidental spillage where surface HC inputs are very high and also in landfarming soils where high amounts of HC were shown to migrate down to more than 5 m (Calabrese et al., 1993). The HC that penetrate in deep horizons of soil can be degraded only extremely slowly due to anaerobic conditions.

The TOC increase in treated plots was attributed to the leaching of water-soluble metabolic products resulting from biodegradation of HC (Oudot et al., 1989). The input was in the order of 1.4% of the initial C load,

in concordance with previous results (Oudot et al., 1989). The nature of these compounds, e.g., organic acids and aromatic ketones is partially known (Langbehn and Steinhart, 1995; Cozzarelli et al., 1995). Microbial counts showed that the drainage water contained microorganisms in the same order of magnitude as the control soil. Hence, part of these soluble compounds may be partially or completely biodegraded in the drainage water and in the subsoil.

Influence of Drill Cuttings on Soil Fertility and Plant Productivity

The mineral components of the drill cuttings modified the chemical fertility of the treated plots. Due to the high content of lime in the cuttings, the Ca content (CaO, $CaCO_3$) of the plots M and H increased significantly. This caused a slight elevation of the pH that did not inhibit the biodegradation process. In H, lime was two times higher than in control resulting in a decrease in P, probably due to complexation by Ca^{2+} (Morel, 1980). The resulting P concentration was still high enough to ensure microbial degradation and plant growth, though maize exhibited P deficiency at the 3 to 4 leaves stage. At that time, the plant roots were all contained in the surface Ap horizon where the concentration of DC was at a maximum, thus possibly causing a perturbation in the plant growth. Three months later (13–14 leaves stage), root profiles showed that plants cultivated on treated plots had developed longer roots (50–60 cm) than in the control (30 cm). Phosphorus deficiency was no longer visible at this stage, most likely because maize used P in the less contaminated lower horizon. The soil treatment also decreased the K content of the Ap horizon, but the periodic fertilization maintained the nutrient to a level high enough to sustain microbial activity and plant growth. The organic compounds (HC and additives) of the DC significantly increased the organic C content in the upper 0 to 20 cm, as is observed when crude oil is deliberately spread on the topsoil (Tedesco et al., 1988; Udo and Fayemi, 1975; Watts and Corey, 1982). During the 2-yr experiment, DC did not affect plant germination and density. Udo and Fayemi (1975) found that germination of maize was impaired by crude oil at a concentration near 3%. Other workers (Ilangovan and Vivekanandan, 1992; Terje, 1984) have shown that plant germination responses vary greatly from one plant to another. In this study, the HC content in soil did not exceed 2000 mg kg^{-1} (0.2%), and germination rates were not lowered. However, growth and grain yield of maize were reduced in DC treated plots, probably due to phytotoxic effects of HC (Amakiri and Onofeghara, 1983; Baker, 1970). One year later, the remaining HC concentration still caused a reduction in yield and plant height of wheat, possibly because the plant root system was restricted to the 0- to 25-cm layer where HC concentrations were highest (200–800 mg kg^{-1}). After 2 yr, the residual HC concentrations in soil were low enough (100–200 mg kg^{-1}) to have no noticeable effect on pea development. At the concentrations of DC that were applied, fuel oil HC were not detected in the seeds of the three crops.

This study showed that extensive landfarming, i.e., spreading of low rates of oily wastes may be an alternative to the classical landfarming with heavy HC loads. It permits cultivation of plants with slight detrimental effects and does not necessitate fertilization or soil treatment other than those required for agricultural practices. The efficiency of biodegradation of fuel oil hydrocarbons is high and minimal environmental impact is ensured. However, it has been shown that some polycyclic recalcitrant HC persist as stable organic matter. Also vertical infiltration of HC is not negligible, the intensity and depth of migration being higher when initial loading rate increases. These points have been rather overlooked in most previous landfarming experiments. This experimental study must not be considered as a guideline for landfarming operations, which are under local legal licenses.

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